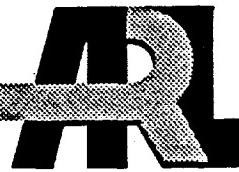


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ARMY RESEARCH LABORATORY



Component P_{K/H} (P_{D/H}, P_{I/H}) Exercise,
26 March 1992

J. Terrence Klopcic

ARL-SR-8

March 1994

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Contents

I.	Introduction	1
A.	The Problem	1
B.	Participants	2
C.	Agenda	3
II.	Definition of the Problem	4
III.	Identification of the Customer	7
IV.	Branch Presentations	8
i.	ASB	8
ii.	GSB	8
iii.	VMB	9
iv.	LTTB	10
v.	IBAB	10
vi.	SAB	11
V.	Desired Solution	12
A.	Taxonomy	12
1.	Considerations	12
2.	Component $P_{K/H}$	12
B.	Needs/Solution	14
1.	Define the Component	14

2.	Sensitive Areas	15
3.	Component Kill Criteria	15
4.	Criteria Delivered	16
5.	Output	16
VI. Other Observations/Recommendations from the Meeting		18
VII. Summary		19
A.	Accomplishments	19
B.	Lessons Learned on Workshop Technique	19
1.	Good	19
2.	Could Have Been Better	20
3.	Applicability of TQM	20
Appendix A		23
Appendix B		45
Appendix C		53
Appendix D		89
Appendix E		93
Appendix F		101
DISTRIBUTION LIST		139

List of Figures

- 1 Defining the Problem 6

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I. Introduction

On 26 March 1992, at the direction of the Chief, Vulnerability/Lethality Division (VLD), USAABRL, a workshop was held to address problems related to the evaluation of component $P_{K/H}$. To the extent possible, the workshop was intended to employ the concepts and methods of Total Quality Management (TQM). This report details the conduct and the results of that exercise.

A. The Problem

The problem to be addressed at the workshop arose in the vulnerability process step called "Component $P_{K/H}$ ". In all high-detail vulnerability analyses conducted at the BRL, the process of determining a damage state for the target consists of several steps. First, the functioning of the threat warhead is evaluated. In the case of weapons such as blast warheads, this functioning may cause a damaging environment at the location of a critical component of the target. In the case of weapons such as a shaped charge, the functioning of the warhead may cause a shielding component (e.g., the armor) to be perforated with subsequent impact of a critical component by the residual fragments from the penetrator. Also, the penetration process may cause fragments to be spalled off the back surface of the shield itself, and these fragments may strike a critical component. In any case, the functioning of the threat warhead, directly or indirectly, may cause a damaging environment to impinge upon a critical component. Evaluation of the strength of that environment is an important topic in terminal ballistics that is beyond the scope of this paper.

However, having evaluated the strength of the potentially damaging environment at the location of a critical component, it remains to evaluate the probability that the environment will sufficiently damage the component to render it ineffective ("killed") for the purposes of the analysis. Techniques for accomplishing this crucial step have independently evolved in a somewhat haphazard and inconsistent way in the various branches of the VLD (as well as throughout the vulnerability world). The ramifications of this situation have been to produce component $P_{K/H}$ s that may be quite subjective and analyst-dependent.

It was to alleviate this situation that Dr. Paul Deitz, Chief, VLD, BRL, directed that a process action team (PAT) be formed to address the Component $P_{K/H}$ problem. The goal of the PAT was to formulate a program that would provide the analytical tools necessary to evaluate component $P_{K/H}$ values con-

sistently throughout the division.

The purpose of this report is to describe the activity of this process action team, to record its results, and to comment on the efficacy of the process in providing solutions to technical problems in an organization like the VLD.

B. Participants

Organization and facilitation of the process action team was effected by Dr. J. Terence Klopcic of the VLD. Administrative and logistical support and arrangements were provided by Mrs. Barbara Snapp.

The first order of business was to identify the participants. To this end, a rough sketch of the problem to be addressed and the method of solution was provided to each of the six branch chiefs in the VLD. Each branch chief was then asked to nominate two individuals from his branch that were knowledgeable in the technical area (component $P_{K/H}$) and sufficiently senior to represent their branch's interests in the exercise.

The individuals who participated in the exercise, by branch, were:

- a. Air Systems Branch (ASB)
 - Walt Thompson
 - Bob Walther
- b. Ground Systems Branch (GSB)
 - Chuck Huenke
 - Larry Losie
- c. Integrated Battlefield Assessment Branch (IBAB)
 - Ed Davis
 - Terry Klopcic

d. Logistical and Tactical Targets Branch (LTTB)

- Jim Hunt
- Loren Kruse

e. Systems Assessment Branch (SAB)

- Tyler Brown
- Rick Grote

f. Vulnerability Methodology Branch (VMB)

- Scott Henry
- Robert Shnidman

In preparation for the workshop, all participants were scheduled for the BRL Quality Improvement Process (TQM) Sessions being given to all BRL employees by the BRL Quality Management Office.

C. Agenda

The workshop was held in a conference room at the Sheraton Inn in Aberdeen. The one-day session began at 0800 and concluded at 1630.

In preparation for the workshop, the organizers had prepared a "strawman" agenda for the session. The first order of business was to confirm the completeness of the agenda. As decided by the workshop, the agenda for the exercise was as follows:

- I. Define the Problem
- II. Identify the Customer
- III. Presentations by Branches of Current Methods
- IV. Conceptualization of the Desired Solution
- V. Identification of Tasks to Effect Solution

II. Definition of the Problem

Briefly, the problem to be addressed by the workshop dealt with the evaluation of the status of a target component which has been subjected to the effects of a damage mechanism. While informal inter-branch cooperation has arisen in places, there are not techniques for evaluating component status that are generally accepted by all the branches. Utility codes to help evaluate component status (after particular threat/component interactions) are scattered; input data are incomplete and largely anecdotal. Evaluations appear to be largely subjective and traceable only through the memory of the evaluator.

On the other hand, arriving at a problem definition that was sufficiently succinct for the cooperative efforts of thirteen individuals was not particularly easy. In particular, there have arisen two markedly different descriptions for the characteristics of the fragments that impinge upon components that are interior to a target: one based upon fragment mass and speed and the other based upon hole-making capability ("Direct Lethality"). Although recognizing the inherent importance of fragment description in the component $P_{K/H}$ problem and the eventual need to address the issue, the organizers also recognized the potential morass into which the workshop could wander if fragment characterization was included in the problem definition. Therefore, as part of the workshop preparation, an agreement was reached among various participants and the Chief, VLD to treat fragment characterization as an input to be addressed later. It was important to assure that all participants understood this definition.

On the output side, it was also necessary to define the limits of the problem to be addressed. First of all, it had to be made clear that the problem being worked was to find/develop a common *methodology* for evaluating component $P_{K/H}$; the problem did not involve the component $P_{K/H}$ values themselves.

Apparently more confusing for some individuals was the difference between component $P_{K/H}$ and the effect that component loss had upon the target system. Using terminology from a recent VLD report,¹ the three stages (levels) of vulnerability analysis and the operators that map points from one to the other were reviewed. In that terminology, the O'23 operator - which quantifies the functional importance of a particular component in overall system performance - was specifically excluded from this workshop.

¹J.T.Klopsteg, M.W.Starks and J.N.Walbert, *A Taxonomy for the Vulnerability/Lethality Analysis Process*, BRL Report, recently released for printing

The result of this part of the exercise was a diagram, drawn on the "butcher-paper", similar to that in Figure 1.

The group went on to list the problems within the dashed box in Figure 1. In particular, they listed:

1. Disjoint approach
2. Specific problems common, with differences
3. Areas include fuel, ammo, crew
4. Development of tools/programs/algorithms must cover:
 - What is a component
 - Kill mechanisms
 - Aggregation of mechanisms

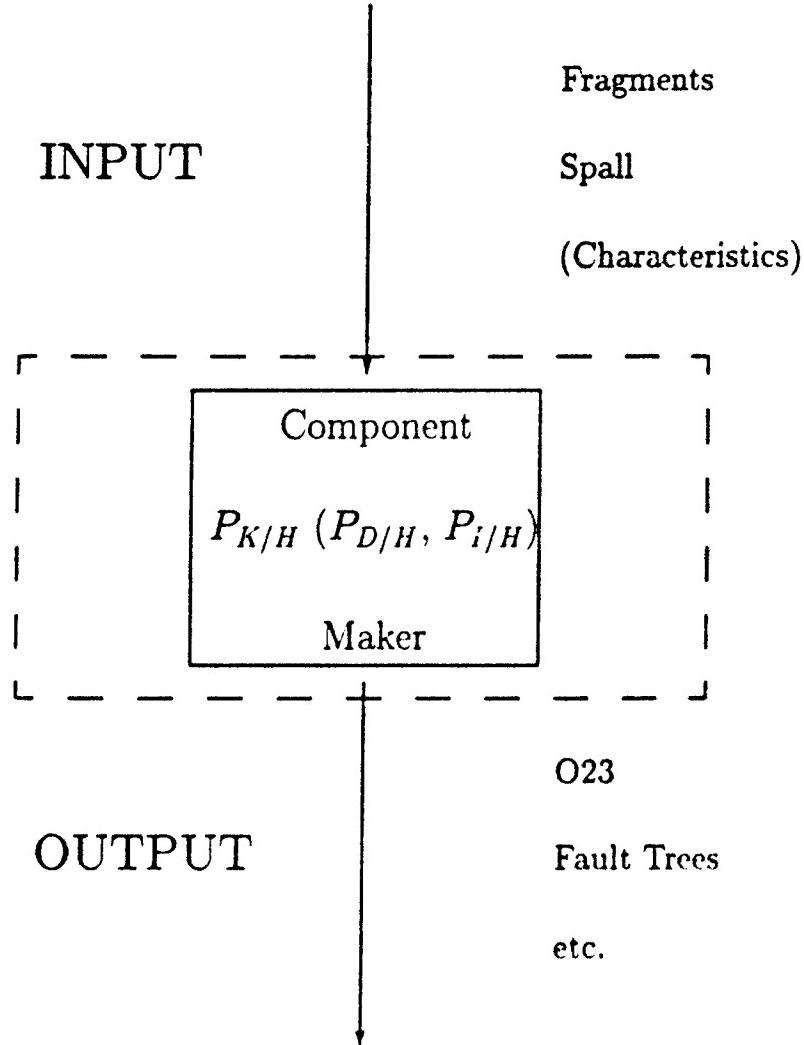


Figure 1: Defining the Problem

III. Identification of the Customer

The next action was to identify the customers for the methodology that was to be developed. Influenced by the recent TQM training, the attention first turned to the external customers. It was felt that the external customers might include all the services, where the user would be at least a journeyman analyst. Mr. Jim Flint (Eglin AFB) was listed as an example of an external user. The possibility of gaining eventual JTCG/ME approval was recognized. Additionally, contractors, vehicle and aircraft manufacturers, and weapon designers were recognized as potential users.

Interestingly, the identification of external users served a valuable role in completing the definition/bounding of the problem. In the discussion, the potential customers that were disallowed made it clear that the effort was to be spent on the development of an evaluation *method*, and not on evaluations themselves.

Of most importance, however, was the identification of the internal customer. It was agreed that the (hypothetical, composite) internal (VLD) customer is an analyst with some experience. The user would have seen and handled damaged components and probably witnessed some live fire test shots. The "core" methodology to be developed would be constructed for such an analyst.

In order to attend to the needs of the more inexperienced analysts, it was decided that a "wrapper" may be constructed around the core $P_{K/H}$ program to provide guidance, default values, etc. However, it was agreed that experience - and consultation with those who are experienced - was indispensable. Therefore, a totally neophyte-level methodology would be ill-advised.

IV. Branch Presentations

The next agenda item was the presentation, by each branch, of its current methods of evaluating its equivalent of component $P_{K/H}$. This was a most valuable exercise, resulting in identification of tools that formed the starting point for the proposed solution. This exercise also added to reaching a common definition of the problem. For example, it was through the ASB presentation that it became apparent that the term $P_{D/H}$ was used in ASB to mean "Component $P_{K/H}$ ".

Viewgraph presentations (scheduled for 20 minutes each) were given by ASB, GSB, VMB, LTTB, and IBAB. In consideration of the time, SAB waived its presentation, noting that its techniques were largely covered by GSB.

A short synopsis of the most salient points of each presentation follows. Hard-copy viewgraphs of the presentations are included in the appendices.

i. **ASB** The ASB presentation was broken into two parts: engines and other components. For engines, algorithms have been derived for relating power loss to hole size in various engine sections. During the presentation, the evaluation of $P_{D/H}$ ($P_{K/H}$) for other components by scaling from actual firings was discussed. A more detailed write-up on $P_{D/H}$ evaluation is included with the presentation viewgraphs in Appendix A.

ii. **GSB** GSB's basic tool for evaluating component $P_{K/H}$ is COMPKIL. However, since COMPKIL outputs are inappropriate for SQuASH, GSB has worked with VMB (Shnidman) to adapt it for direct lethality (see below). GSB closed with a list of issues:

- What is a component?
- What is meant by a component $P_{K/H}$?
- There are deficiencies in COMPKIL.
- Always use (directionally) random hits?

The viewgraphs used by GSB are reproduced in Appendix B.

iii. **VMB** Bob Shnidman gave concise presentations on a couple of issues. First, he reviewed the function of COMPKIL, the inputs for which are fragment mass and velocity. He then went on to briefly describe the adjustments made to make COMPKIL into PKCOMP, the outputs of which are SQuASH compatible. Essentially, the two codes use penetration equations to calculate the amount of component sensitive area that can be sufficiently "holed". In both cases, the user must input such information as presented areas, sensitive areas and barriers. The codes differ in their penetration equations - mass-velocity vs. direct lethality.

As an aside, Bob also discussed the differences that he has found in penetration equations used within the community. In particular, disagreement between the predictions of the FATEPEN2 and THOR equations led to the associated recommendation listed in section VI..

Bob then went into the VMB efforts. There are two major issues here: direct lethality, and the high resolution modeling in which VMB has implemented it. The workshop organizer insisted on keeping these issues separate, since each has potentially wide applicability independent of the other.

Under the direct lethality, Bob described the empirical formulae used to predict hole size vs. depth in a witness pack as a function of armor and impinging threat. The portion of the formulism that corresponds to component $P_{K/H}$ is embodied in the function " $K(t,h)$ ", loosely definable as the sensitive area in which a component kill will result from a hole of size h at depth of penetration t . (Although specific details are beyond the scope of this report, it was significantly noted that K is a *differential* function; i.e. its value gives the *increase* in total component vulnerable area with increasing t .)

Finally, Bob described the VMB work with high resolution modeling of components. A viewgraph was shown of an electronic component that was modeled down to the switches and circuit boards. The code hres.c has been developed to analyze components at that level. Significant doubt was raised about the practicality of modeling many of the components at the high resolution level of detail, especially in those branches that require fast turn-around of foreign (unavailable) vehicles. However, it was appreciated that the high resolution modeling may be an excellent supplement/substitution for actual component testing, with a concomitant savings in time and money.

VMB viewgraphs are reproduced in Appendix C.

iv. LTTB Jim Hunt followed with a description of PKGEN,² a computer code that evaluates the $P_{K/H}$ of a three dimensional representation of a critical system component. It was apparent that LTTB has also done a great deal of work to automate component $P_{K/H}$ generation. PKGEN appears to transcend the "level" of COMPKIL and PKCOMP. The user can input information on the geometry and construction of the component. In addition, PKGEN has the ability to use BRL-CAD - described components to ease the $P_{K/H}$ analysis. It allows a number of kill criteria, viz:

1. fragment mass and/or velocity
2. depth of penetration
3. hole size
4. residual mass at depth
5. kinetic energy and/or momentum transferred
6. mass removal

PKGEN also allows combinations of the above kill criteria using the binary operators AND and OR.

In addition, PKGEN also allows a number of options on the incident fragment directions to be included in the analysis.

Of significant importance is the user-orientation of PKGEN. The code uses windows, help screens, etc. to ease the use of the code by any analyst. Although the code is currently implemented only for Silicon Graphics (SG) Workstations, it is written in C and, except for its SG-specific features, should be quite easily portable to other machines.

The LTTB viewgraphs are reproduced in Appendix E.

v. IBAB Ed Davis then gave a brief, yet comprehensive, look at the personnel vulnerability methodologies, especially that encompassed in the ComputerMan code. The two major observations from that briefing were: The

²James E. Hunt, *Computer-Aided Methodology for Generating Component Probability of Kill Functions*, BRL Report, in draft. See Appendix D.

attendees (and hence, probably, the rest of VLD) were not aware of the sophistication and resulting wealth of data that have been achieved in personnel vulnerability; and, in spite of the marked differences between (highly complex) humans and other system components, the fundamental approach to component $P_{K/H}$ was remarkably similar. In fact, Computer Man may be the ultimate example of the high resolution component modeling espoused by Shnidman, especially since the kill criteria are depth of penetration in the body and critical hole sizes in various sub-components (organs).

Note, however, that the terminology used in the personnel vulnerability community is different than that used for materiel. In particular, the measure of effectiveness of a penetrating injury is $P_{I/H}$. When a crew member is considered as a component (e.g., in the analysis of a weapon system), the $P_{I/H}$ must be interpreted as a component $P_{K/H}$.

The viewgraphs used in the IBAB presentation are reproduced in Appendix F.

vi. **SAB** The SAB representatives considerably waived their floor time, noting that the time was running out and that the other branches had covered the major issues and techniques used in SAB.

V. Desired Solution

The next phase of the workshop addressed the characteristics of a solution to the component $P_{K/H}$ problem that would be of benefit to the envisioned customer. The organizer began this phase by posting a "strawman" taxonomy of the solution that he gleaned as the common elements from the foregoing presentations. This process, corrected/amended by the group, then served as the framework for identifying the specific actions that should be taken to provide the desired solution.

A. Taxonomy

1. Considerations

A number of technical considerations arose in the process of amending the taxonomy of the solution. Some of the salient points to be incorporated into the solution include:

- Effects of multiple fragments (and other kill, damage and incapacitation mechanisms) must be included in the new methodology.
- The new methodology must include – as an inseparable part of the output – an "audit trail" that includes the analytical considerations, reasons and assumptions made in the analysis.
- Since there is an intrinsic connection between a specific target description and its set of component $P_{K/H}s$, there is an unavoidable trade-off between target detail and component $P_{K/H}$ methodology. A most illustrative example is a computer terminal whose soft part is the screen. If modeled as a single component ("terminal"), directionality of the incoming fragments is critical. However, if modeled as two components (soft "screen" and harder "chassis"), the ray tracing inherent in the analysis codes (e.g. SQuASH) will properly account for directional effects. The major conclusion was that the component $P_{K/H}$ analyst must be in the "target description loop".

2. Component $P_{K/H}$

A terse statement of the problem undertaken by the workshop is:

Given a fragment or fragments impinging on a component, evaluate the probability that the component will be rendered non-functional (killed) or, in the case of components such as ammunition and fuel, made to malfunction in such a way as to become a cause for additional damage.

It was observed that, in the case of live fire tests of specific threats against specific components (e.g. as conducted by ASB), the above statement IS the process. The threat is launched at the component and the subsequent component status is evaluated.

However, for analytical evaluation of component $P_{K/H}$, a more involved process was identified. The amended process of the component $P_{K/H}$ is:

0. Define the Component. The $P_{K/H}$ analyst must know the physical regions in the target description that define the component. (See comment on trade-off between component $P_{K/H}$ and target description, above.)

1. Input. Establish the criteria for killing the component. These might include:

- Hole size at depth.
- Material removed.
- Energy or momentum deposited.
- Bending or jamming (currently empirical)

NOTE: All component kill criteria are time-dependent. For example, a small fuel line leak might not constitute a target kill in five minutes but would in five hours. (Of course, in cases such as catastrophic hits on ammunition, the resulting system failure time may be nearly instantaneous.)

2. Input. Determine the sensitive areas. Techniques might include:

- High resolution modeling
- "Calibrated eyeball" (as done for COMPKIL)

3. Code/methodology. Evaluate the criteria delivered by the threat. Algorithms might include:

- For hole size and depth of penetration
 - * Penetrations equations.
 - * Direct Lethality.

- Basics physics for energy/momentum deposition.
 - etc.
4. Output. The post-analysis presentation and output utilities might include:
- Data visualization (graphs, silhouettes, etc.)
 - "Sanity checks against reality".
 - Easy (VLD-level?) database entry.
 - Packaging of output for shipping.
 - * Assumptions, audit trail
 - * Formatting
 - * etc.

B. Needs/Solution

Guided by the above list (which was torn off and prominently hung on the wall), the workshop identified the following needs to be addressed by the Chief, VLD to solve the component $P_{K/H}$ problem.

1. Define the Component

1. Administratively, get the $P_{K/H}$ analyst into the target description loop. (This is already the default mode in LTTB and ASB in that most analysts take a system vulnerability study "from womb to tomb".)
2. If the analyst starts with an existing target description, he may, in the process of evaluating component $P_{K/H}$ s, determine that more detail is needed. (e.g. A component in the description is too diverse and should be described as more than one component.) In such cases, an SOP should be established so that the analyst can get the component upgraded quickly.
3. The concept of a utility code that would help the analyst make such target description upgrades himself was specifically discarded. It was universally felt that the existing codes (mgd) and existing personnel capable of using the existing codes were adequate, given the administrative direction/priority.
4. REVISION CONTROL on target descriptions. It is essential that the precise target description used in an analysis - accounting for any component upgrades - be automatically recorded and accompany the results.

2. Sensitive Areas

The workshop expressed a need for:

1. BRL-CAD - driven interface tool. This tool should give, as a minimum:

- Presented areas of components
- Line-of-sight thicknesses
- HARDCOPY (from Laserprinters)
- Density
- Weights (?) (Possible value for shock kills.)

2. Library of component damage. This could include:

- Pictures
- Data
- (Expert) descriptions of analytical considerations

3. Museum of actual damaged components. This display, which could be set up in a warehouse on "The Island", would be invaluable to neophytes. Included with each display item must be a description of the threat the produced the damage.

3. Component Kill Criteria

1. Library of component damage, as above.

2. Database of kill criteria. This database must include:

- Component description - including dimensions
- Component function being disrupted.
- The failure mode. NOTE: This also includes the time-to-failure.
- Target containing the analyzed component
- Target description/version containing the component
- The study for which the kill criteria were derived
- Who did the criteria determination
- How was it done (Calculation, experiment, engineering judgment)

- Mechanism causing component failure
- "Pointers" to references, mgd pictures, publications, etc.

The database must be easily updated.

IT MUST BE NOTED: The workshop felt that experimental data was needed before this database could be fully filled.

4. Criteria Delivered

It was agreed that PKGEN, the code currently being used in LTB, appeared to offer an excellent starting point for the development of a code/methodology for general VLD use. However, significant work would be required. This included:

1. Augmentation for calculation of factors needed for the direct lethality methodology; in particular, calculation of $K(t,h)$
2. Construction of utility code to read COMPKIL inputs
3. Expansion (future) for other kill criteria, such as multi-fragment criteria
4. Institutionalization, which includes:
 - Establishing responsibility for code maintenance, adaption for other terminals, etc
 - Configuration control
 - Distribution, both in and out of the BRL

It was also pointed out that the high resolution work now being done in VMB should continue with an eye toward providing data in special cases and, more routinely, providing calibration points for PKGEN. High resolution component $P_{K/H}$ s could also be assembled into a library to be used as would a library of experimentally measured values.

5. Output

1. Visualization tools. These should include:
 - Silhouettes showing sensitive area in component

- Graphs, tables and ranking of component $P_{K/H}$ within a group
- 2. Packaging utility to meet the needs identified in section A., above
- 3. Component $P_{K/H}$ Database, which must include all auxiliary information that accompanies the data.
- 4. Automated data preparation for above database.

VI. Other Observations/Recommendations from the Meeting

During the course of the workshop, a number of recommendations were made which, although not falling within the precisely defined limits of the workshop, were deemed important enough to be included in this report. These included:

- An introductory course for new employees in which they could actually observe component damage would be an excellent complement to the tools recommended above.
- The VLD staff are generally ignorant of the progress that has been made in personnel vulnerability. We should have a division colloquium on the subject. (In subsequent discussions, it was brought out that such colloquia are successful only if the administration makes such a colloquium "the business of the day", requiring all personnel to attend and dispensing other activities.)
- There are significant discrepancies between the predictions of the THOR equations currently in use in the VLD and other penetration algorithms. In particular, the FATEPFN2 equations have been used by NSWC, Dahlgren and by DRI (on JTCG/ME-sponsored studies). These discrepancies are particularly significant in the analysis of subsequent barrier penetration. The VLD should conduct a study to carefully compare these equations, relate them to experimental data, and adopt the more accurate ones. Clearly, the ubiquitous influence of the penetration equations in vulnerability assessments places high priority on this task.
- The sensitivity of vulnerability analyses to the choice of incident fragment direction (random, upper hemisphere, specific direction, etc.) is not generally known. Knowledge of that sensitivity could guide the amount of effort to be placed upon directional considerations in PKGEN.

VII. Summary

The Component $P_{K/H}$ workshop was conducted to recommend a program to solve a particular VLD-wide problem. An ancillary benefit was to determine the effectiveness of the TQM techniques being promulgated within the BRL.

A. Accomplishments

The workshop defined the problem and the process involved in reaching a specific solution. Guided by that process, the workshop identified tools to be developed that would result in a methodology for component $P_{K/H}$ evaluation generally applicable throughout the VLD. These tools included:

- Databases for Sensitive Areas, Component Kill Criteria and Component $P_{K/H}$. The possibility of combining these into one database was observed.
- A museum of actual hardware for the training of inexperienced analysts.
- A general computer code, built upon the existing PKGEN, with augmentations as noted.

B. Lessons Learned on Workshop Technique

1. Good

In general, the feelings of the participants the workshop were (as communicated to the organizer) very positive. One of the more general observations was the manifest benefits of inter-divisional communication. It was felt by some that such communication was lacking in the VLD; "We don't always know what the other branches are doing." This problem is apparently exacerbated by the current dispersion of VLD personnel.

There was general agreement that the workshop was quite a success. Unexpected agreement was reached on a solution to a fairly complicated and personalized problem. It was also a source of pride to several that the workshop was able to get as far as it did in a single session.

The organizers feel that the size of the workshop was about right. Everyone had a chance to express his views at any time without completely stopping the flow of the meeting. Judging by the breadth of the discussions, it appears that most significant points were presented.

The facilities and amenities were universally appreciated. This is solely to the credit of Mrs. Snapp, whose efforts must be acknowledged.

2. Could Have Been Better

There were lessons to be learned as well. In retrospect, however, the organizers recognize that the major lessons are no different than those pertaining to the running of any conference. Foremost of these was the need to stick a bit more closely to the time schedule set out for the meeting. It is essential to hold prepared speakers to their allotted time. Else, it is too easy to lose the momentum generated at the onset of the session. This results in a "dead" audience for the subsequent speakers and jeopardizes completion of the task.

It also became pretty quickly apparent that "the magic marker" had to stay in the hand of the organizer. Taking turns at the butcher-paper was an unfair burden to place on participants who had not been involved in the planning, tentative agenda preparation, etc.

At first, the amount of time needed to define (limit) the problem and define the customer seemed excessive. However, in light of the clear necessity of limiting this problem and the success in coming to a conclusion about the problem once it was defined, the organizer feels that the time spent on agenda items 1 and 2 was well invested.

3. Applicability of TQM

It was noted by the organizer that TQM is not so much a technique as it is an attitude. That attitude, characterized by concern for the expectations of the customer, was apparent in the workshop.

The TQM training given to the BRL lists five essentials of the Quality Process:

1. Quality is Consistent Conformance to Customer's Expectations.

2. Measurements of Quality are Through Indicators of Customer Satisfaction versus Indicators of Self-Gratification.
3. The Objective is Conformance to Expectations 100% of the Time.
4. Quality is Attained through Prevention and Specific Improvement Projects.
5. Management Commitment Leads the Quality Process.

Rating the workshop on this scorecard, one would observe:

1. It is impossible at this time to evaluate the degree to which the eventual results of this workshop will satisfy the VLD customers. Attempts were made at the outset to identify those customers and their desires. At another level, a customer of the workshop was the Chief, VLD, who commissioned it. An open presentation of the results of the workshop is planned, at which time that customer satisfaction can be gauged. However, the fact that the workshop did carry through to a product is certainly a "plus".
2. It is important that the implementation of the solutions developed in the workshop continue to take the customers in mind. In particular, it is essential that any codes and databases developed be user tested throughout the VLD. Perhaps of more importance, it is essential that projects undertaken to implement the solution be completed in a timely fashion. It will not help anyone to have these tools become reality next century.
3. Same as 2
4. This workshop was a specific improvement project, as recommended by TQM.
5. Finally, most of management's role remains to be shown. The idea for the workshop and the provision of the facilities was all done by management. But that was a minimal investment. The proof of management's commitment to the TQM process will show most clearly in the reception and implementation of the workshop results. If the solution developed by the workshop is acted upon by management - or, if not, if the reasons for significant changes are shared in a cooperative way with the participants - those in the workshop will recognize that they were, in actuality, "empowered"; i.e., they would then be:
 - a. *Informed* of the problem

- b. *Included*, not only in words but in fact, in the solution
- c. *Authorized* to actually make decisions. The workshop was definitely a DECISION-MAKING ACTIVITY. However, a decision ignored isn't worth many TQM points.
- d. *Equipped* through the subsequent program to implement the solution
- e. *Justified* in having their expectations met.

That will be the biggest test of the TQM Process.

Appendix A

***P_{D/H}* Write-up and Briefing Package: ASB**

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Pd/h development for aircraft targets depends upon the failure mode applicable to a particular type of component.

For mechanical components, the primary failure modes are severance, jamming, seizure and loss of mesh, and material removal. The failure mode "severance" applies to flight control linkages, hydraulic actuator input and output links, drive shafts, and rotor blades. The failure mode "jamming" applies to hydraulic actuator cylinders, flight control rotating components, and engine components. The failure mode "seizure and loss of mesh" applies to gearbox gears and bearings, swashplate bearings, and bearings in general. The failure mode "material removal" applies to engine components, airframe structure, and rotor blades.

For fluids, the primary failure modes are leakage, sustained fire, hydrodynamic ram, and rupture. The failure mode "leakage" applies to fuel cells and lines, engine fuel components, hydraulic lines, pumps, and reservoirs, oil tanks, pumps, coolers, and lines, and gearbox housings and sumps. The failure mode "sustained fire" applies to those components listed for "leakage" with the exception of gearbox housings and sumps. The failure mode "hydrodynamic ram" applies to fuel cells and hydraulic reservoirs. The failure mode "rupture" applies to pressurized containers used for oxygen, nitrogen, etc.

For Aircrew, the primary failure modes are incapacitation by penetrating injury and incapacitation by blast overpressure.

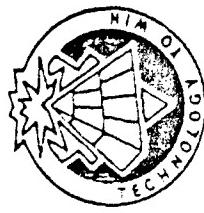
For ammunition containers, missile warheads, and motors, the primary failure mode is detonation or deflagration of ordnance.

Development of a matrix of Pd/h values for each failure mode-component combination is dependent on a number of factors. As the simplest example, "severance" is dependent on thickness of diameter, wall thickness, and loading. A combination of penetration equations and simple algorithms is used to determine the Pd/h values. Development of Pd/h values for sustained fire is a more complicated process, since it is dependent on at least eight factors (See following viewgraphs). However, these factors have been quantified for use as input to Pd/h development, and are well documented.

The development of Pd/h values for all failure modes have as their basis test firings, and are normally well documented in the Qualification Reports and Joint Live Fire Reports pertinent to a particular aircraft.

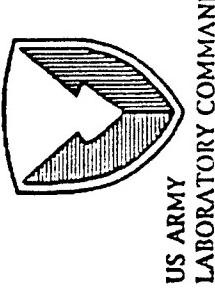
For complex critical components such as engines or transmissions, multiple potential damage effects and interactions are incorporated in the Failure Modes

and Effects Analysis (FMEA) which precedes selection of P_d/h and P_k/h values. These values track the various damage effects which can be imposed on the component, or separate parts of it, ranging from (for example) external case perforation by light threats, internal disruption by increased threats up to obliteration and secondary damage by thrown parts by heavy threats. Although target availability historically lags behind emerging technology, new systems usually retain some features or similarities of the old, and BRL possesses a large test data base to support P_d/h generation. Over time, a select group of algorithms have been developed to quantitatively relate component functional degradation to threat-induced kill criteria for particular components. As appropriate, they relate component kills to critical hole-size, threshold kinetic energy, leakage rate/fluid depletion, fuel ingestion tolerance, bearing run-dry failure time, etc. Given the particular failure mode of critical component is achieved (P_d/h), the probability of a particular type of kill of the vehicle (P_k/h) is derived on the basis of component singly or multiply vulnerable status, vehicle controllability in degraded condition, nearness to the ground, and other factors, which are defined for the target in a specified configuration in terms of Kill Boundary Curves.



ROTARY WING AIRCRAFT VULNERABILITY ANALYSIS

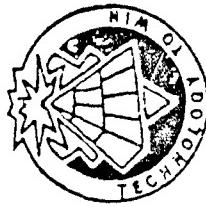
BALLISTIC RESEARCH LABORATORY



Robert E. Walther
Air Systems Branch

Vulnerability and Lethality Division

U.S. Army Ballistic Research Laboratory



KILL DEFINITIONS IN VULNERABILITY ANALYSIS

US AIR FORCE
LABORATORY
AND
BALLISTIC RESEARCH LABORATORY

KILL LEVELS:

Attrition: Loss of Manned Control Resulting in Loss of the Aircraft

Forced Landing: Aircraft Must Land or Attrition Will Result

Mission Abort: Aircraft Returns to Base - Mission Not Completed

SINGLY and MULTIPLY VULNERABLE:

Singly Vulnerable: A Component is Singly Vulnerable if Damage to it
Alone Results in a Given Level of Aircraft Kill

Multiply Vulnerable: A Component is Multiply Vulnerable if Damage to it
and At Least One Other Component is Required
for a Given Level of Aircraft Kill to Result



BASIC DEFINITIONS IN VULNERABILITY ANALYSIS

BALLISTIC RESEARCH LABORATORY

US ARMY
LABORATORY
IND

VULNERABLE AREA (Av) :

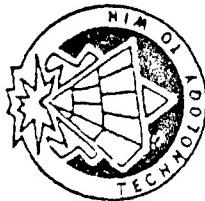
$$Av = \int \int Pk/h (x,y) dx dy , \text{ where}$$

Pk/h is the Probability of Kill Given a Hit, and
dx dy is an increment of Presented Area (Ap)

PROBABILITY of KILL GIVEN A HIT (Pk/h) :

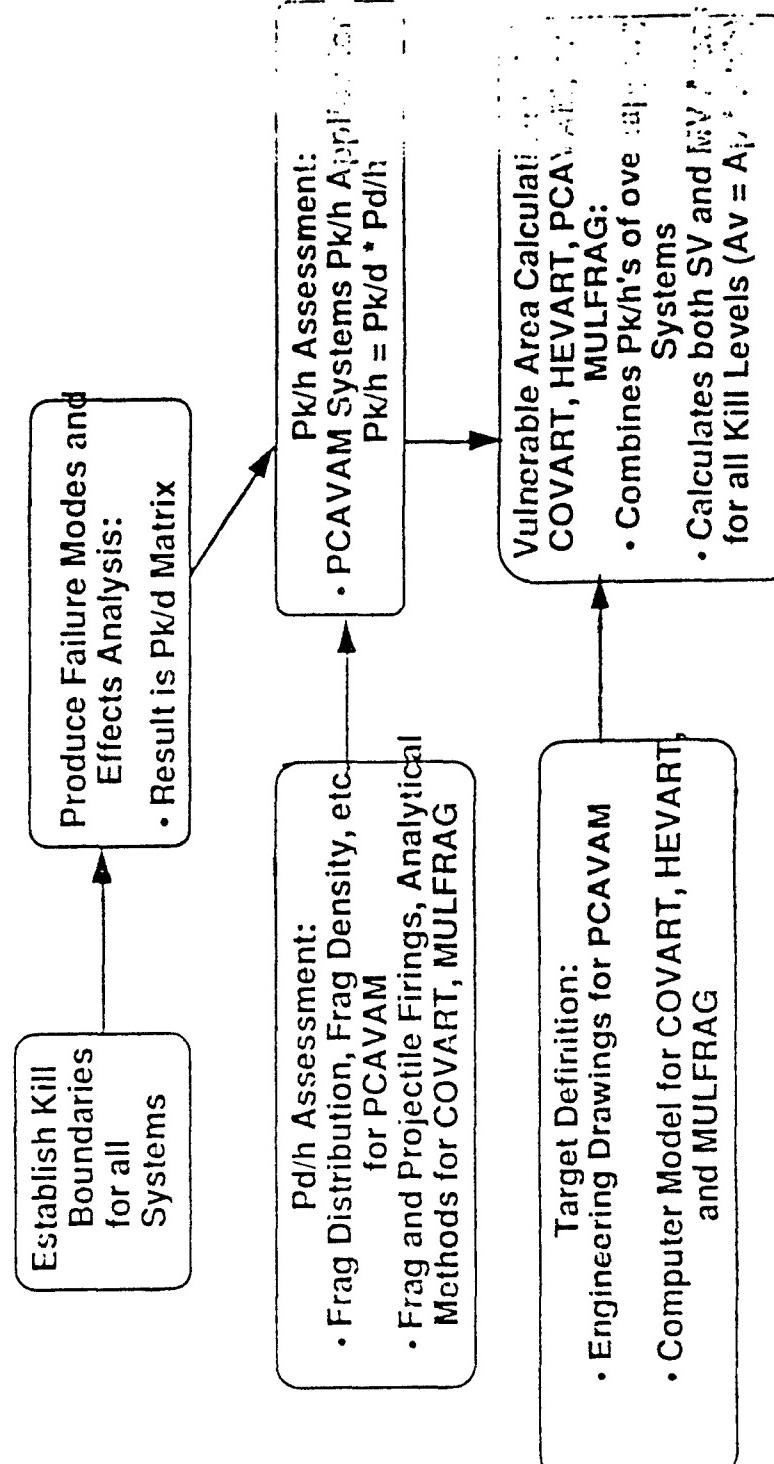
$$Pk/h = Pk/d * Pd/h, \text{ where}$$

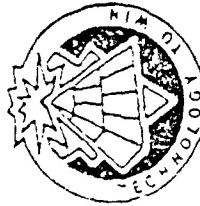
Pk/d is the Probability of Kill Given Damage, and
Pd/h is the Probability of Damage Given a Hit



VULNERABILITY ANALYSIS PROCEDURE

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US ARMY
LABORATORY AND
TECHNOLOGY





UH-60A KILL BOUNDARIES

NON-LINEAR RESEARCH LABORATORY

US AIR FORCE
LABORATORY

- IMMEDIATE POWER LOSS (IPL) - ONE ENGINE
- IMMEDIATE POWER LOSS (IPL) - BOTH ENGINES
- DELAYED POWER LOSS (DPL) - ONE ENGINE
- DELAYED POWER LOSS (DPL) - BOTH ENGINES
- TAIL ROTOR THRUST LOSS
- TAIL ROTOR PITCH CONTROL LOSS - PRESENT SETTING
- TAIL ROTOR PITCH CONTROL LOSS - 7.5 DEG.
- TAIL ROTOR PITCH CONTROL LOSS - VARIABLE, UNCONTROLLED
- TAIL ROTOR BLADE LOSS - > 50%
- TAIL ROTOR BLADE LOSS - 10% - 50%
- TAIL ROTOR BLADE LOSS - < 10%
- STABILATOR CONTROL LOSS

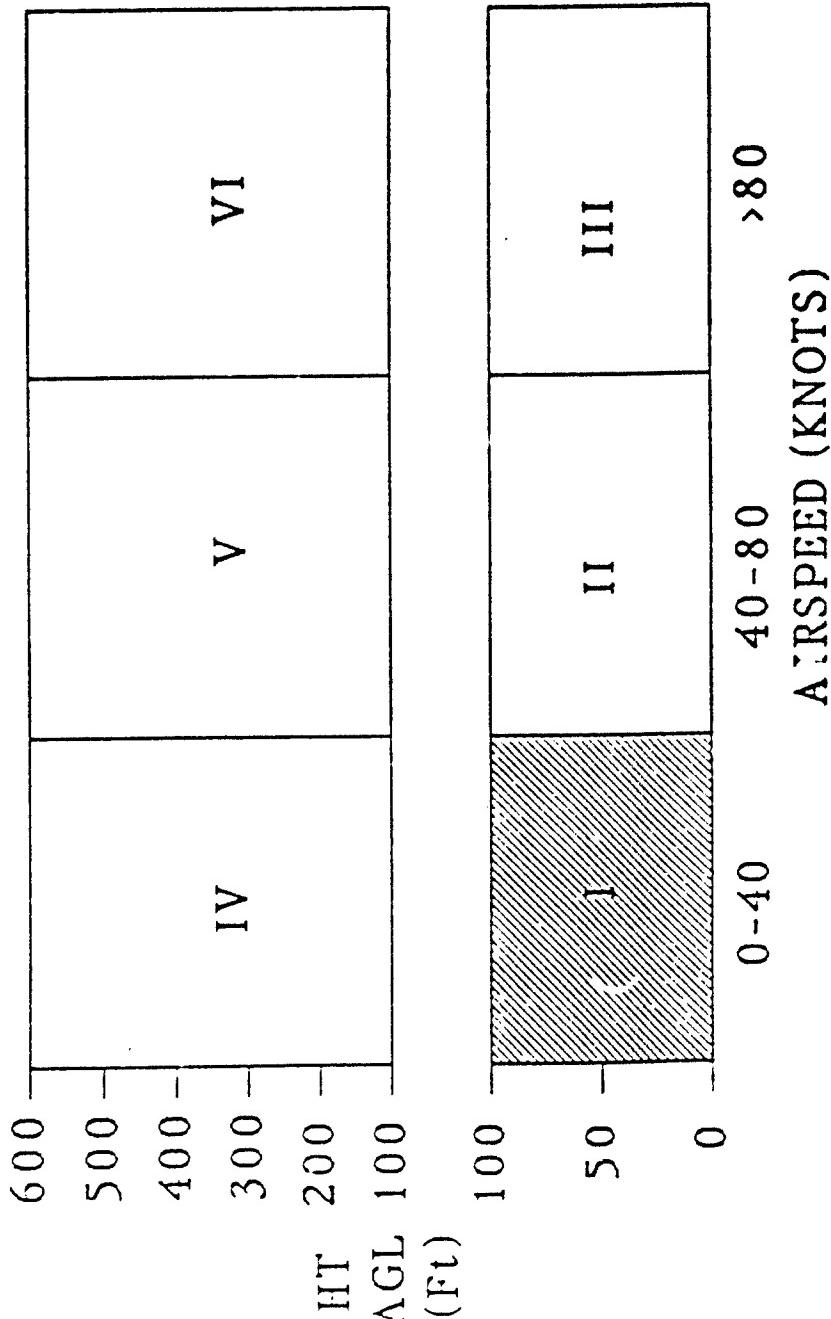


ZONE DEFINITION FOR KILL BOUNDARIES

US ARMY
LABORATORY AND
TEST CENTER

BALLISTIC RESEARCH LABORATORY

4000 FT / 95 DEG



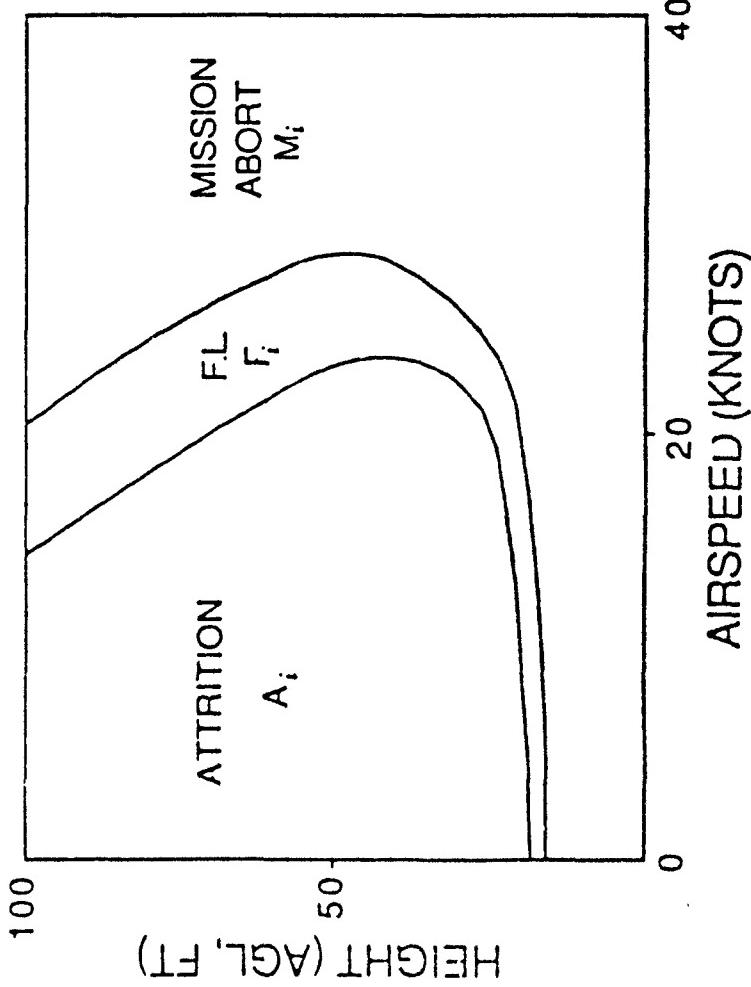


BOUNDARIES FOR ATTRITION,
FORCED LANDING, AND MISSION ABORT
KILLS: IPL ONE ENGINE
GROSS WEIGHT XXX LBS

BALLISTIC RESEARCH LABORATORY

ME

40000 FT/ 95° DAY



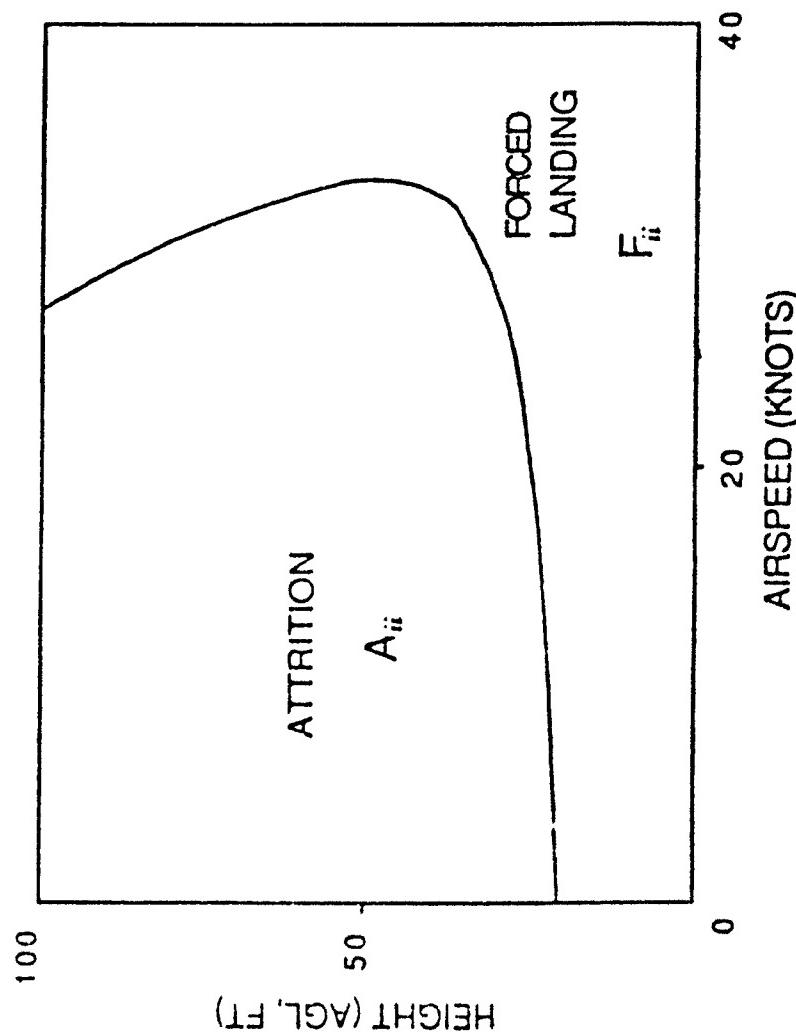


BOUNDARIES FOR ATTRITION
FORCED LANDING, AND MISSION ABORT
KILLS: IPL BOTH ENGINES
GROSS WEIGHT XXX LBS

US ARMY
LABORATORY

BALLISTIC RESEARCH LABORATORY

4000 FT/ 95° DAY



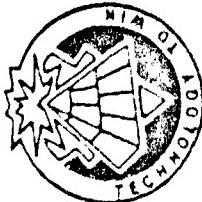
FMEA PROPULSION



U.S. ARMY
LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

SYSTEM #	FUNCTION	DESCRIPTION	FAILURE MODE
Left Engine - 1 Right Engine - 2	Inlet Section	Channeled air to Engine Compressor.	Jam, Material Removal, or Foreign Object Ingestion.
Left Engine - 3 Right Engine - 4	Compressor Section	Deliver High pressure air to Hot Section Module.	Sufficient damage to compressor, bearings, or blades to cause engine power in (a) < 30 sec. (b) > 30 sec.
Left Engine - 5 Right Engine - 6	Engine Output Shaft	Transfer power from Power Turbine Drive Shaft to Transmission Input Module.	Sufficient damage to bearing, or power to the transmission.
Left Engine - 7 Right Engine - 8	Combustor	Convert heat air mixture to high pressure gas.	(a) > 30 sec. Engine self protection. (b) Sufficient damage (dependent on fuel cause signal loss of engine power).
Left Engine - 9 Right Engine - 10	Gas Generation Turbine	Gas Generation Turbine and Auxiliary Gas Unit.	Sufficient damage to turbines, or other blades to cause engine power in (a) < 30 sec. (b) > 30 sec.
Left Engine - 11 Right Engine - 12	Power Turbines	Generate power for motor.	Sufficient damage to turbines, or other blades to cause engine power in (a) < 30 sec. (b) > 30 sec.
Left Engine - 13 Right Engine - 14	Power Turbine Drive Shaft	Transfer power to Engine Output Shaft.	Sufficient damage to intermediate shaft power to the transmission.
Left Engine - 15 Right Engine - 16	Fuel Filter, Fuel/Oil Cooler, Hydromechanical Control Unit, Sequence Valve, Fuel Modulator and HP Fuel Lines.	Conditions and mixes fuel to engine.	(a) Ignition of Fuel Initiated by - Sustained Fire. (b) Leaking of Fuel without Sustained Fire. (c) Loss of engine power.
Left Engine - 17 Right Engine - 18	Fuel Boost Pump	Provide suction head of fuel to engine.	(a) Destruction of HFC. (b) Leaking of fuel.
Left Engine - 19 Right Engine - 20	Electrical Control Unit	Regulates and monitors engine performance.	No effect (Control indicates full function only)
Left Engine - 21 Right Engine - 22	Air/Oil Cooler, Tank Pumps, Filter, Lines, Relief Valves, Chip Detector, Air/Oil Cooler, Tank Pumps, Filter, Lines, Relief Valves, Chip Detector.	Engine Lubrication	(a) Mechanical Damage or leakage of Oil without Sustained Fire. (b) Ignition of Oil Initiated by Sustained Fire. (c) Ignition of Oil from Air/Oil Cooler or Tank



Failure Modes Applicable to Mechanical Components

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US ARMY
LABORATORY COMMAND

Failure Mode

- Severance

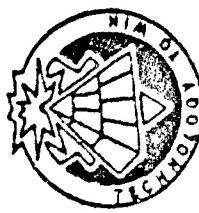
Component Type

- | | |
|-------------------------|------------------------------------|
| Flight Control Linkages | Actuator Input & Output Links |
| Drive Shafts | Rotor Blades |
| Actuator Cylinders | Flight Control Rotating Components |
| Engine Components | Gearbox Gears & Bearings |
| Swashplate Bearings | Engine Components |
| Airframe Structure | Rotor Blades |

- Jamming

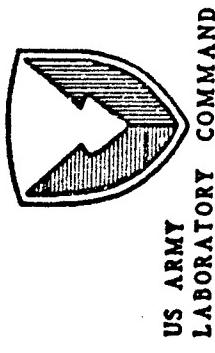
- Seizure & Loss of Mesh

- Material Removal



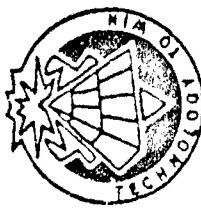
BALLISTIC RESEARCH LABORATORY

Failure Mode: Sustained Fire



Pd/h for Sustained Fire is dependent upon:

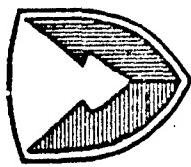
- Probability of incendiary function (for API projectiles)
- Probability of flash (for fragments)
- Air-Gap between function or flash and flammable fluid
- Type material containing fluid (metal, rubber bladder, degree of self-sealing, or other)
- Type of flammable fluid (JP-4, JP-5, Hydraulic fluid, oil)
- Pressure or Suction feed (for fuel lines)
- Type and thickness of protection (rigid foam, flexible foam, powder packs, ullage inerting systems)
- Detection and Suppression System effectiveness



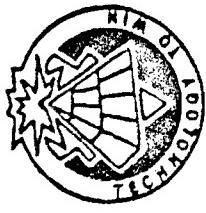
Failure Modes Applicable to Aircrew & Ordnance

US ARMY
LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY



<u>Failure Mode</u>	<u>Component Type</u>
• Incapacitation by penetrating	Aircrew
Injury or blast overpressure	Ammunition Containers,
• Detonation or deflagration of ordnance	Missile Warheads and Motors

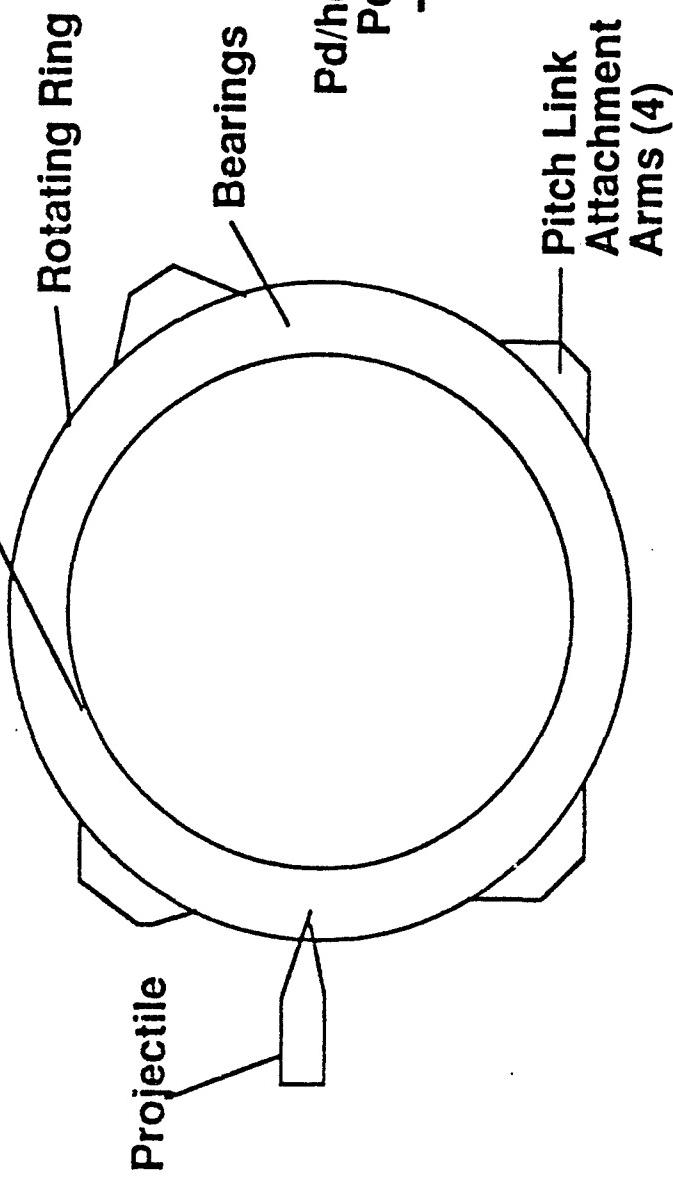


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Failure Mode:

Swashplate Jam & Severance

US ARMY
LABORATORY COMMAND





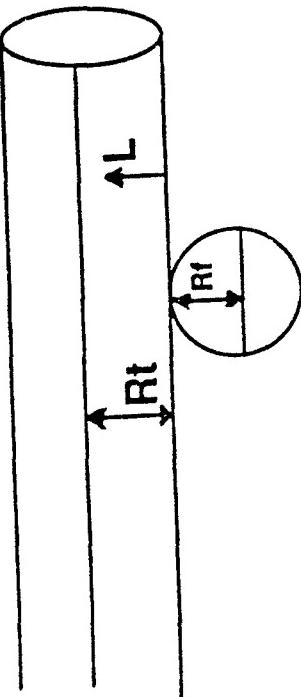
Failure Mode:

Severance Algorithm

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BALLISTIC RESEARCH LABORATORY

Rt = Radius of the Component
Rf = Cutting Radius of the Projectile
L = Distance that needs to be cut to defeat the component
X = Percent of cut needed



$$X = \frac{L}{2Rt}$$

$$Pd/h = \frac{Rf + Rt - L}{Rf + Rt} = \frac{Rf + Rt - 2X Rt}{Rf + Rt}$$

(Assumes Influence Mode)



Failure Modes Applicable to Fluids

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US ARMY
LABORATORY COMMAND

Failure Mode

• Fluid Leakage

<u>Component Type</u>
Fuel Cells & Lines
Engine Fuel Components
Hydraulic Lines, Pumps, & Reservoirs
Oil Tanks, Pumps, Coolers, & Lines
Gearbox Housings & Sumps
Fuel Cells & Lines
Engine Fuel Components
Hydraulic Lines, Pumps, & Reservoirs
Oil Tanks, Pumps, Coolers, & Lines
Fuel Cells
Hydraulic Reservoirs
Pressurized Containers (Oxygen, etc)

• Sustained Fire

• Hydrodynamic Ram

• Rupture

ENGINE FUEL CONTROL KILL PROBABILITIES FOR 60-GRAIN STEEL FRAGMENT IMPACT

(NO ZONE III DAMAGE)
ZONE III DESTRUCT.
ZONE II DESTRUCT.
ZONE I DESTRUCT.
ZONE I PERC.
ZONE II PERC.
ZONE III PERC.

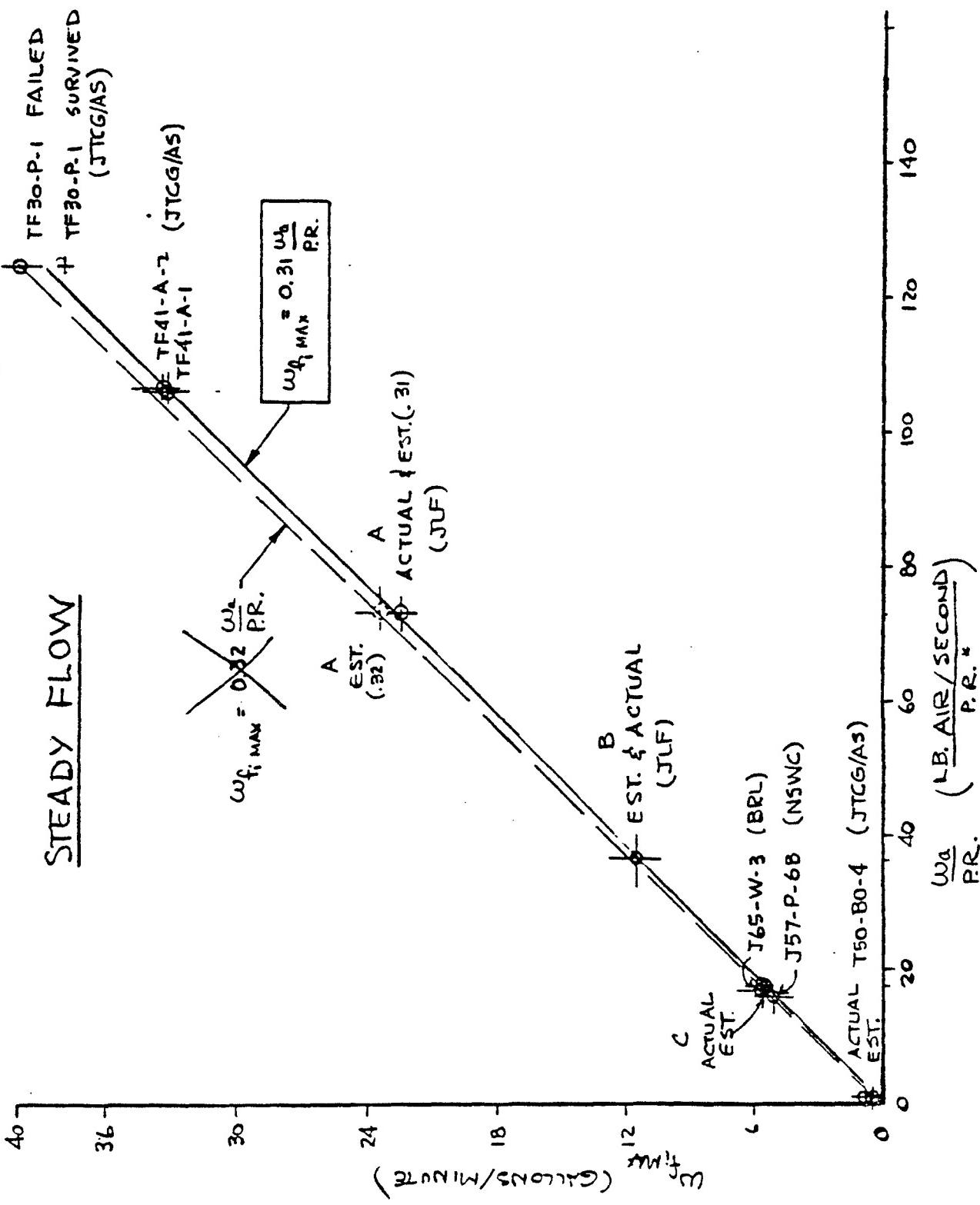
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

COMPONENT-K KILL PROBABILITY

A - PK DATA POINTS USED FOR
STANDARD VS MATRIX

1 2 3 4 5 6 7 8 9
 10^{-3}

STRIKING VELOCITY:



* PRESSURE RATIO OF COMPRESSOR FOR TURBOJETS, OF FAN SECTION FOR TURBOFANS

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Appendix B

Briefing Package: GSB

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GROUND SYSTEMS BRANCH

METHODS OF ESTIMATING COMPONENT $P_{K|H}$

Lawrence D. Losie

26 March 1992

SQuASH EVALUATIONS

- Primary Investigators
GSB - Larry Losie, Jody Robertson
VMB - Scott Henry, Aivars Ozolins
- Targets
Degraded States : Domestreet, Bradley(M2A1)
Live-Fire Predictions : M109, Paladin
- Component $P_{K|H}$
 - For most components, piecewise continuous polynomial functions, generated by PKCOMP, are used
 - Exceptions
 - Personnel External Suspension
 - Main Gun Catastrophic Fuel Kill

ARTILLERY STUDIES

- Primary Investigator - Jim Strobel
- Targets
 - M113
 - M109
 - Bradley
 - Paladin
- Component $P_{K|H}$
 - For most components, two- and four-step functions, generated by COMPKIL, are used
 - Exceptions
 - Personnel
 - External Suspension

SQuASH INTEGRATIONS

$$N_L = \sum_i \int_{t_i}^{\infty} \int_{d_{min_i}}^{\infty} A(h, t, \dots) H(t \mid t_i) K(h \mid t > t_i) dh dt$$

$$P_c = 1 - e^{-N_L}$$

where

A : Debris Model

H : Distribution of random Line-of-Sight

K : Component Kill Functions

OTHER ISSUES

- What is a component ?
- What is meant by component $P_{K|H}$?
- Some deficiencies in COMPKIL methodology
- Should we always use random-hit component $P_{K|H}$?

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Appendix C

Briefing Package: VMB

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VMB COMPONENT PK[H] METHODOLOGY

*Dr. Robert Shnidman
SLCBR-VL-V*

*Vulnerability Methodology Branch
Vulnerability Lethality Division
Ballistic Research Laboratory
Aberdeen Proving Ground, MD
21005-5066*

*Tel. (410) 278-4081 or 278-6656
DSN 298-4081 or 298-6656
FAX (410) 278-5058*

OUTLINE

I. INTRODUCTION & BACKGROUND

- A. History
- B. Algorithms VS Tools

II. THREAT SPACES

- A. Mass & Velocity
- B. Penetration & Hole Size
- C. -Aspect (?)

III. DAMAGE MECHANISMS

- A. Penetration - Penetration Equations
 - 1. THOR
 - 2. FATEPEN2
- B. Shock
- C. Others

IV. HIGH RESOLUTION AND INTERIM MODELS

ALGORITHMS VS TOOLS

- Algorithms and Their Implementation
 - Kill criterion
 - Penetration phenomena
 - Damage aggregation
- Tools
 - Graphics & component visualization
 - Output visualization
 - Input & output editing

THREAT SPACES

- Mass & Velocity Advantages
 - Natural variables for test shots at components
 - Can be used to calculate penetration and mass loss (& fragment breakup) in a variety of materials IF shape and orientation are known (or assumed)
 - Easy to use to calculate air drag
 - Natural variables for some threats
- Penetration & Hole size
 - More directly measurable for behind-armor-debris.
 - Directly related to the primary kill mechanism for many if not most components

TABLE 1 COMPONENT DAMAGE MECHANISMS

COMPONENT	DAMAGING AGENT**	DAMAGING ATTRIBUTES
Crew	Fragments Blast Heat Light Toxic Fumes	Number Mass & Velocity; Penetration Peak Pressure; Time; Overpressure Cal/sq.cm; Time Intensity PPM; Time
Ammunition (including) propellant	Fragments Explosions (Fratricide)	Number; Temperature; Impact Shock Temperature; Overpressure; Fragments
Fuel	Main Penetrator Fragments	Energy; Pyrophoric Ability Number; Penetration; Mass Temperature; Airflow; Ignition Sources; Formation of Pool of Fuel
Optics (including mounting)	Fragments Blast, Shock	Number; Mass & Velocity Impulse
Electronics (inclusive of wiring antennae and containers)	Fragments Blast, Shock	Number; Penetration Impulse
Main Armament	Main Penetrator	Penetration; Hole Size
External Running Gear (including tracks, wheels & Suspension)	Main Penetrator Blast	Penetration; Hole Size Impulse
Engine, Transmission	Main Penetrator	Penetration, Hole Size
Peripherals***	Main Penetrator & Fragments	Penetration, Hole Size; Number, Penetration, Hole Size
Cooling System (including hydraulics & pipework)	Main Penetrator Fragments	Penetration; Hole Size Number; Penetration; Hole Size

NOTES: *This tabulation is liable to modification by reference to new data
to be published in the KTA-13 Catalogue of Component Damage Data.

**Main penetrator has been excluded in cases for which it is wholly
lethal given a hit (e.g for crew).

***For instance, fuel pump, battery and oil filter.

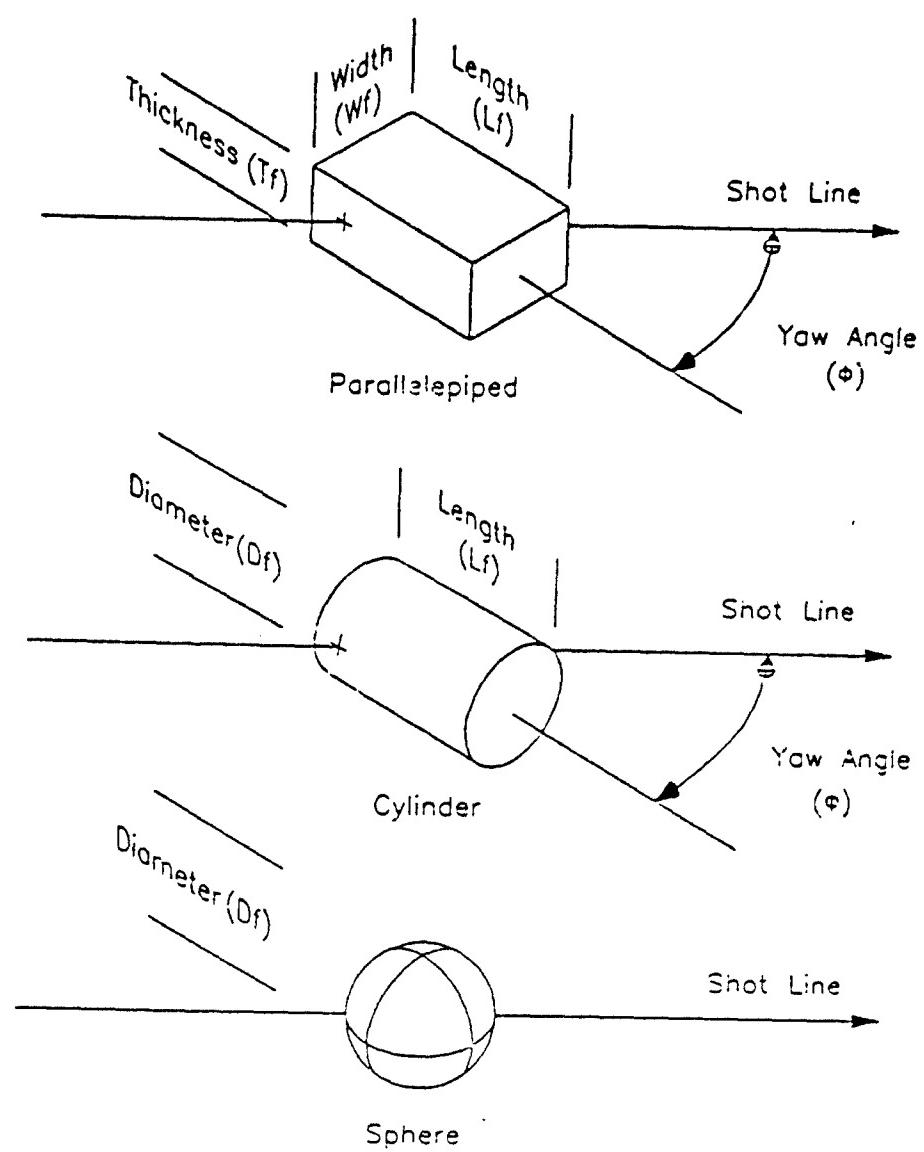


Figure 6. FATEPEN2 Primary Penetrator Shapes and Dimensions.

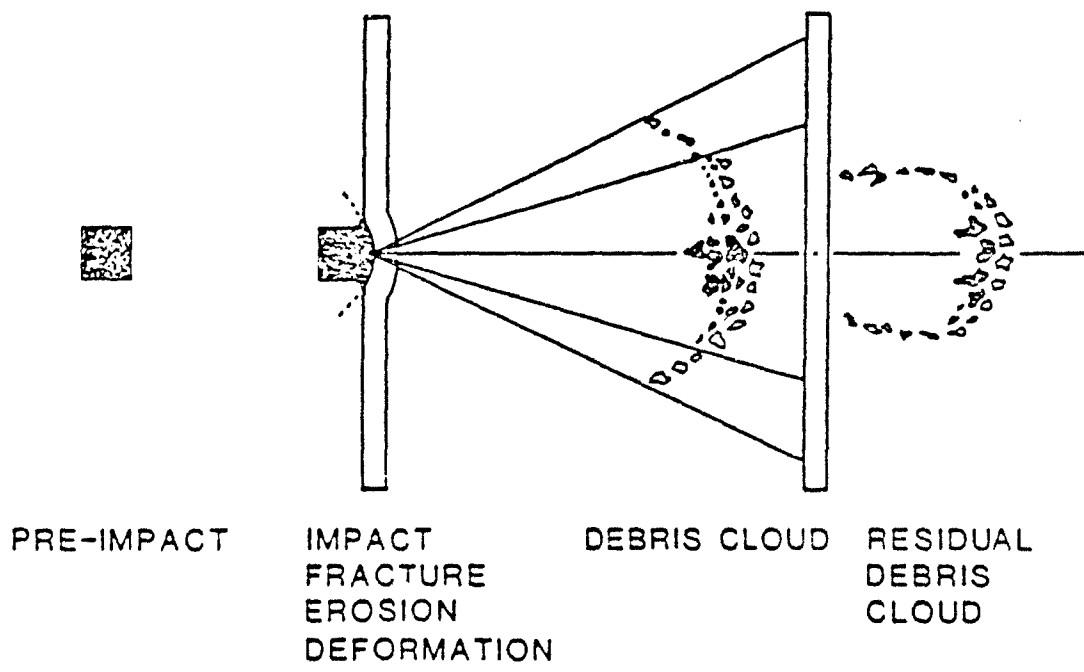


Figure 1. Characteristics of High Velocity Multiple Plate Penetration.

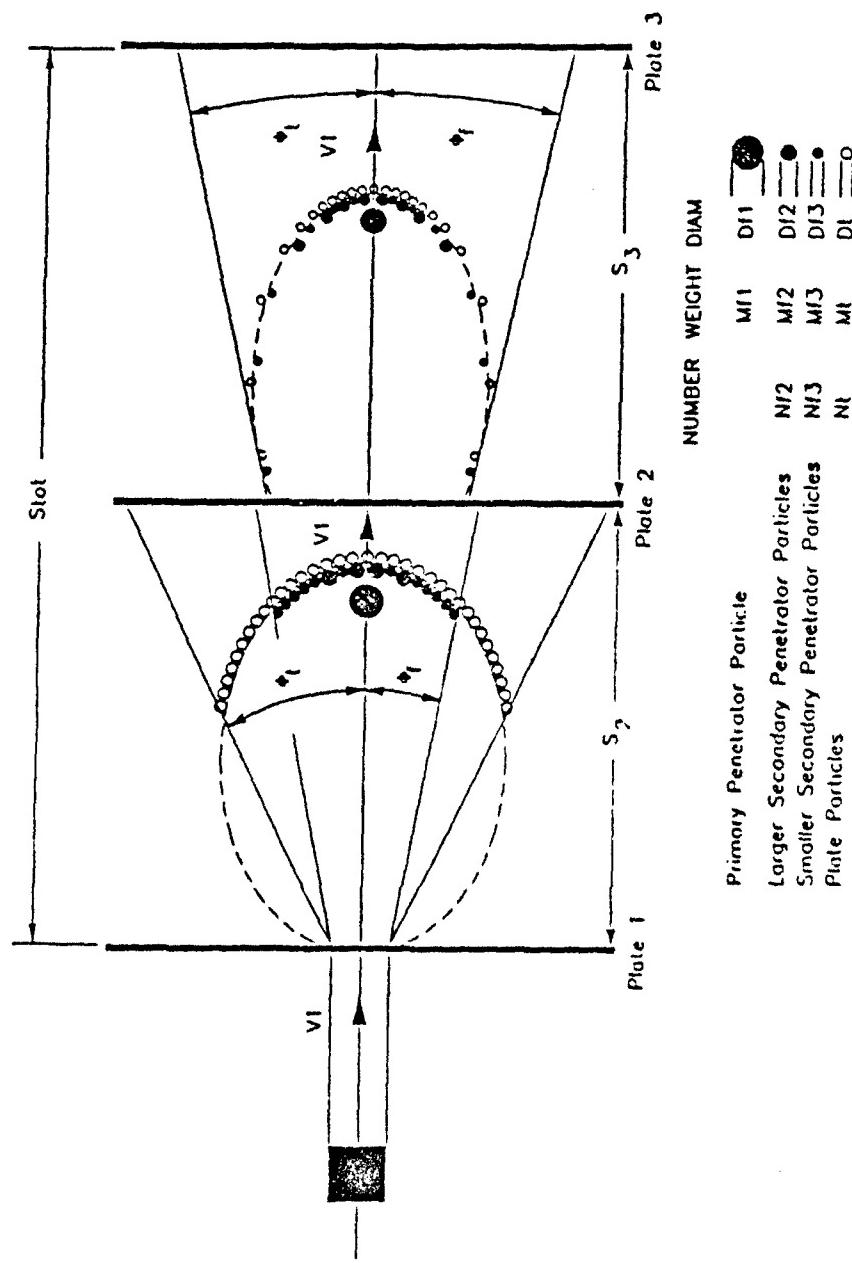


Figure 4. FATEPEN2 Debris Cloud Characteristics.

COMPARISONS OF THOR & FATEPEN2
THRESHOLD VELOCITIES
FOR MULTIPLATE PENETRATION

PLATE ARRAY: 1/32", 1/32", 1/16", 1/16", 1/8"

	m (grains)	v_{TH} (ft/s)	v_{FA} (ft/s)
5 plate	1000	3670	1196
4 plate	300	2996	1055
	1000	1746	704
3 plate	30	5339	1909
	100	2772	1189
	300	1748	819
	1000	1092	548

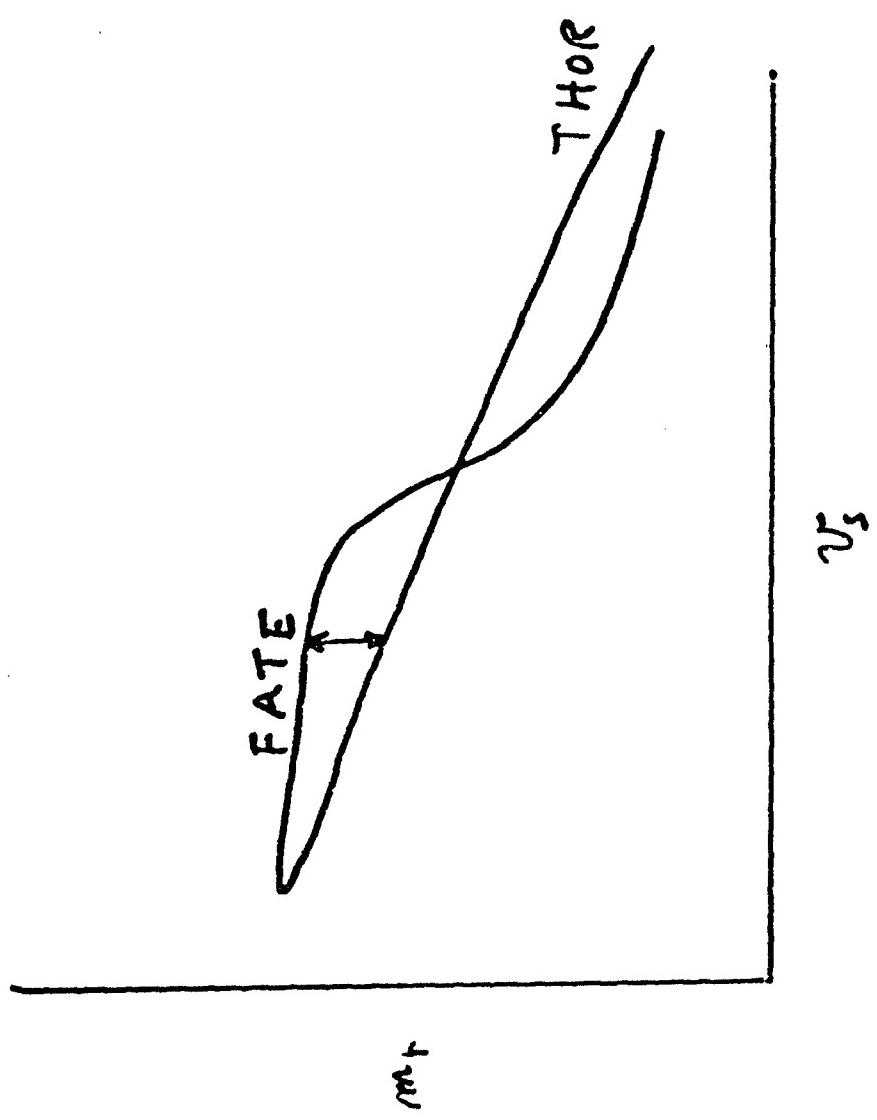
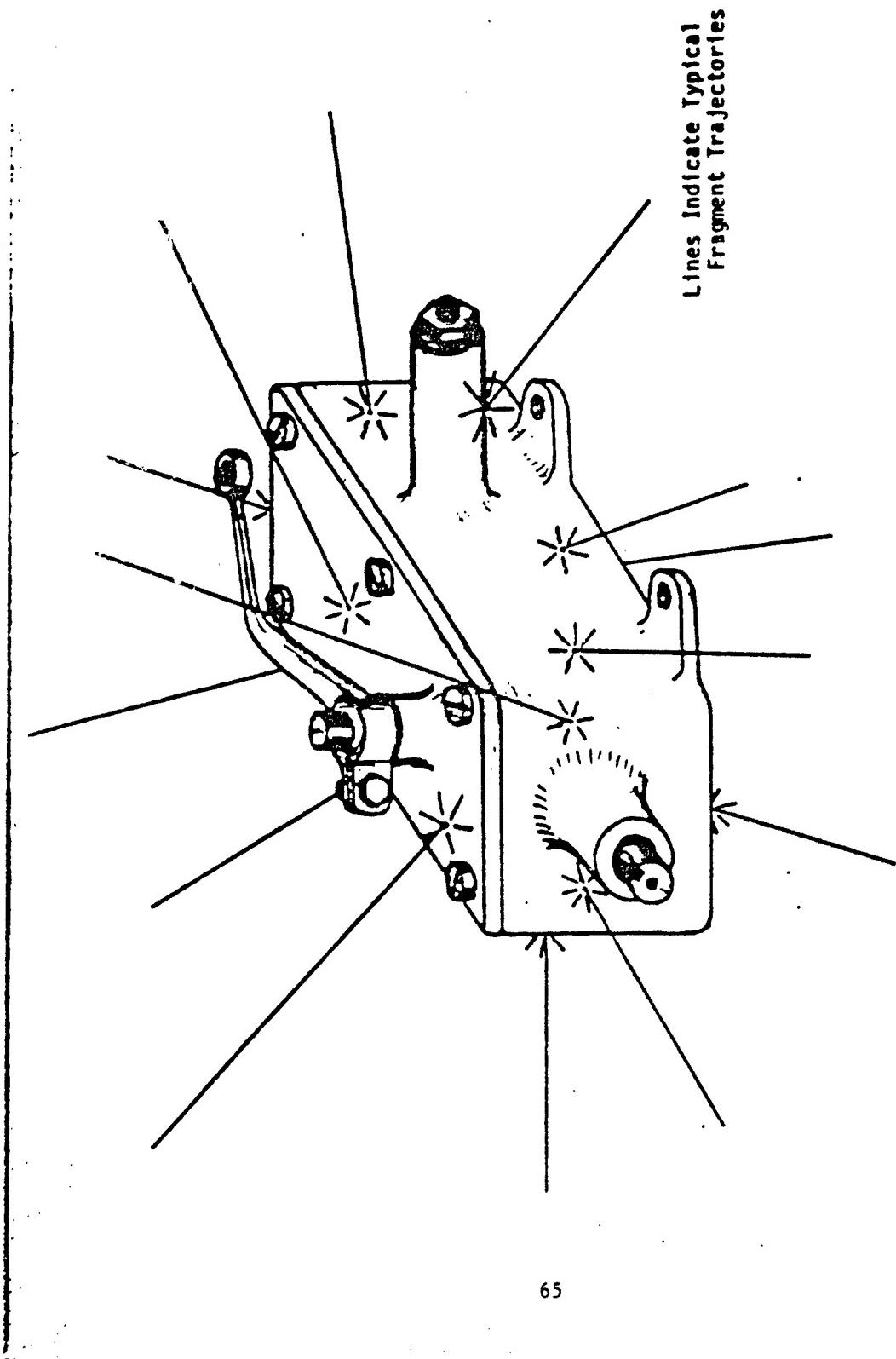
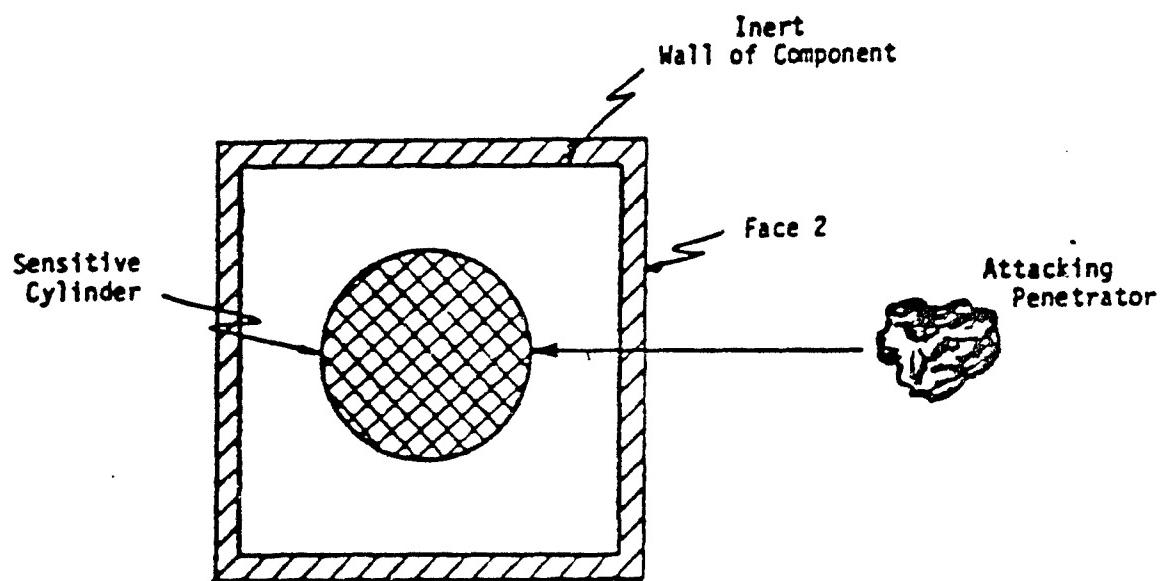


Figure 5. Hypothetical Component Struck by Fragments from Random Directions





Note: Kill requirement is hole size in sensitive cylinder,
not hole size in wall.

Figure 13. Cylindrical Sensitive Area Being Struck by Attacking Penetrator

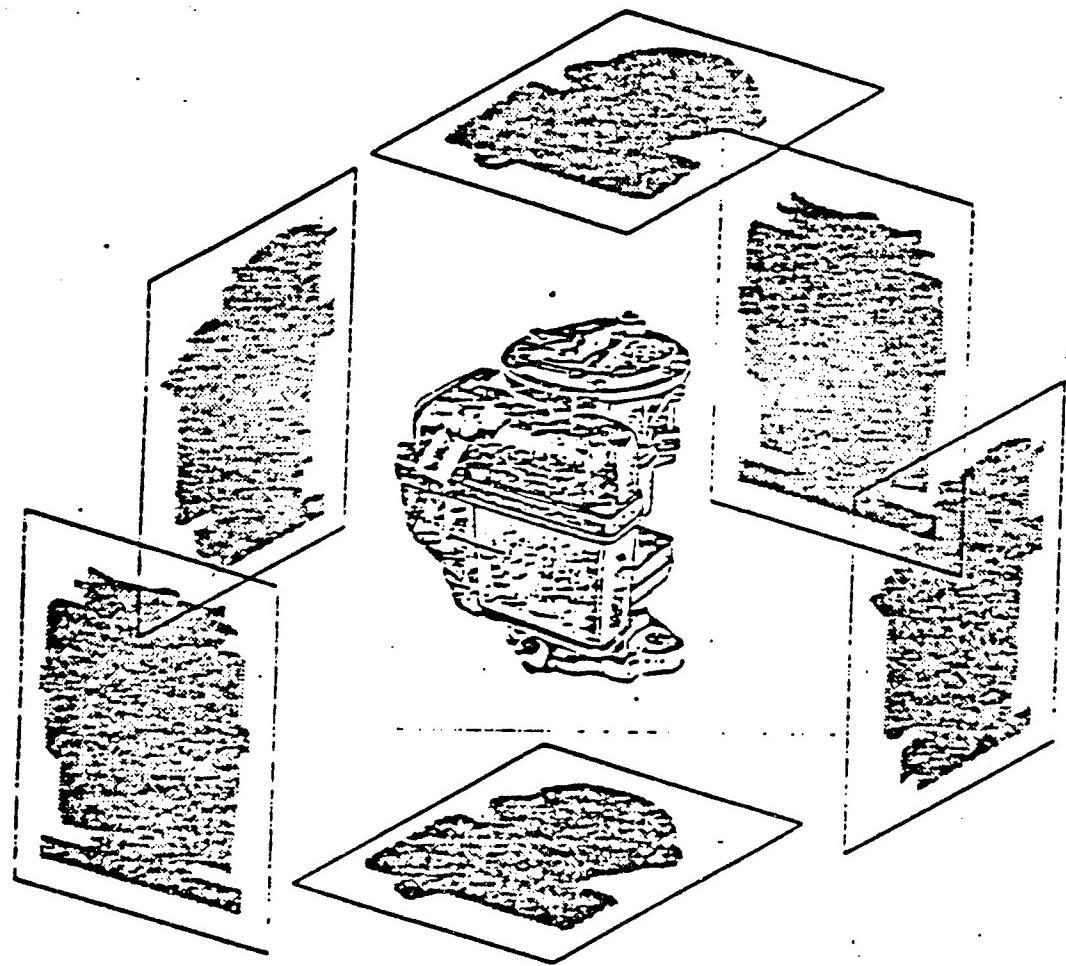


Figure Component Basic Faces

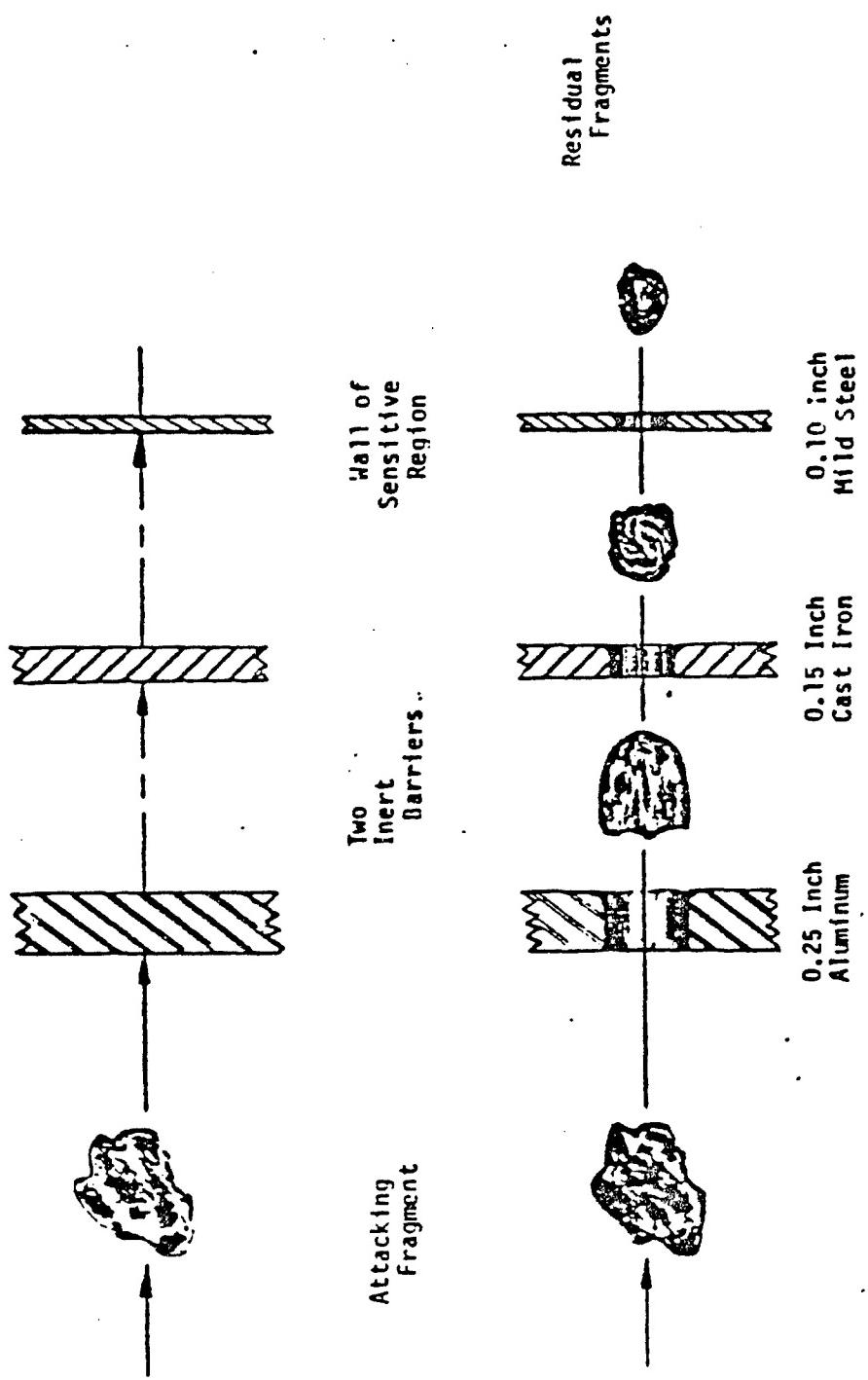
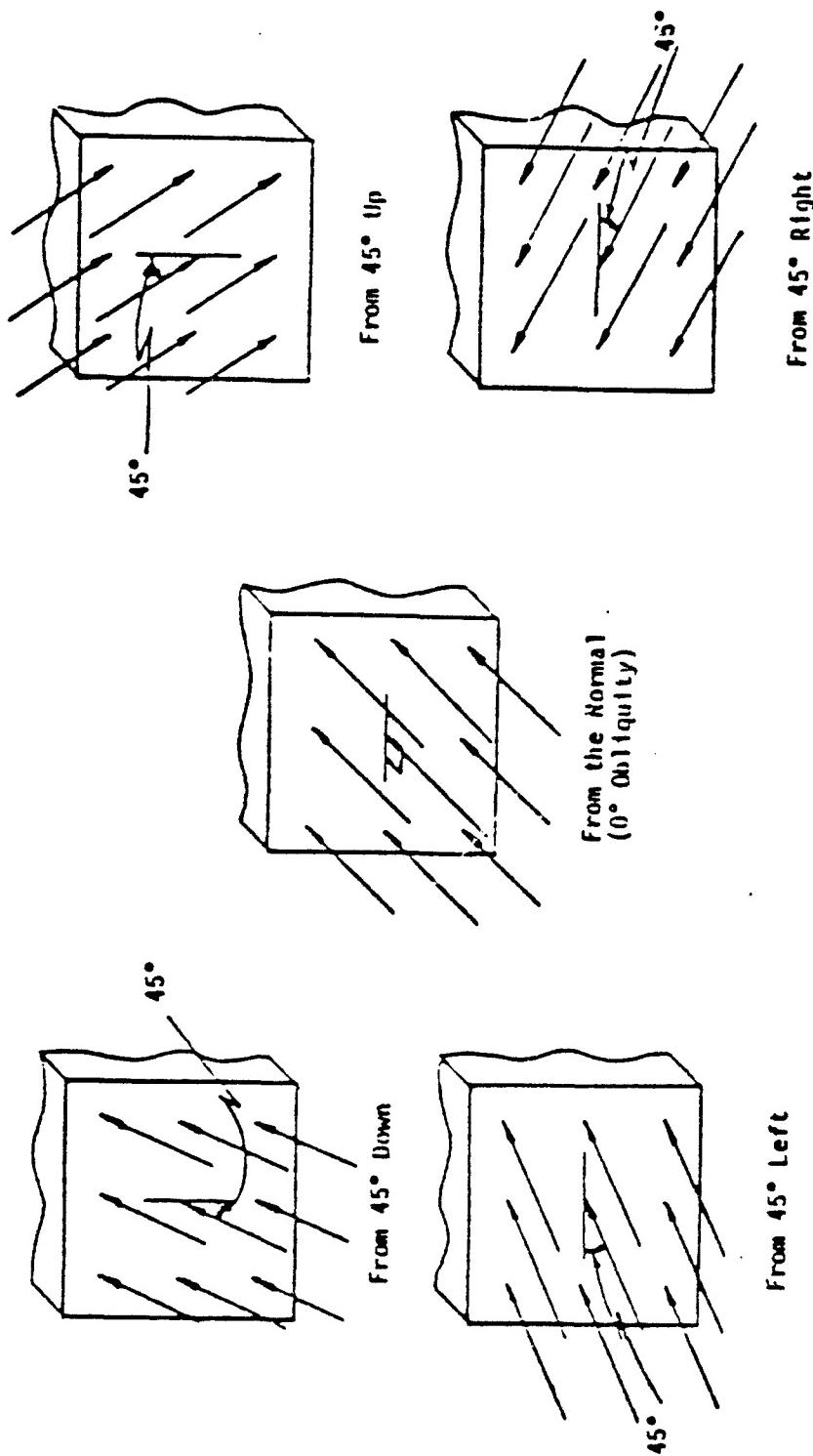


Figure 14. Cross Sectional View of Component Walls Showing
(A) Attacking and (B) Penetrating Fragments



Note: The attack directions on all other faces of the component are the same as those shown here.

Figure 10. Basic Attack Directions on Each Face of the Cubical Component

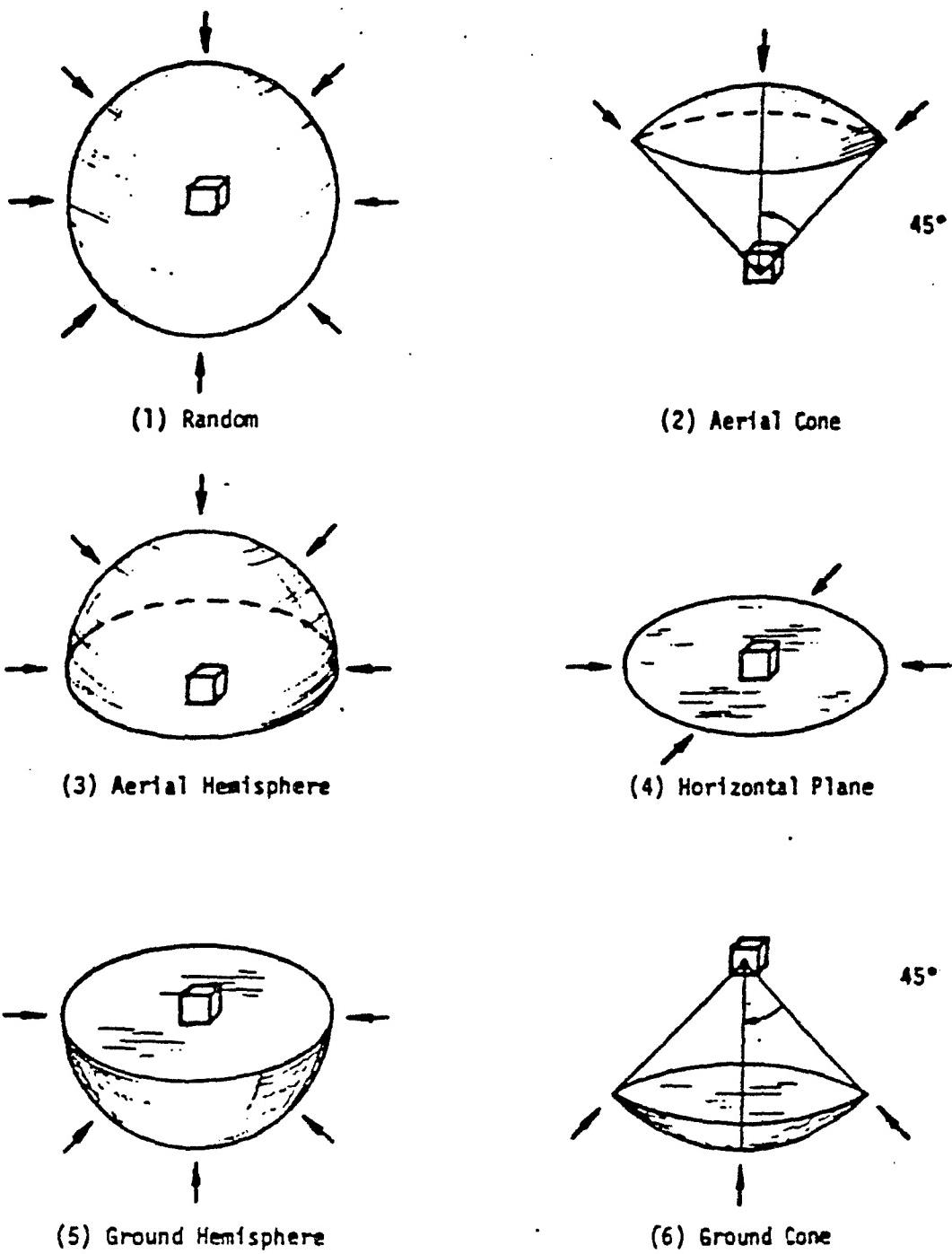


Figure 21. Types of Attack Considered Against Components

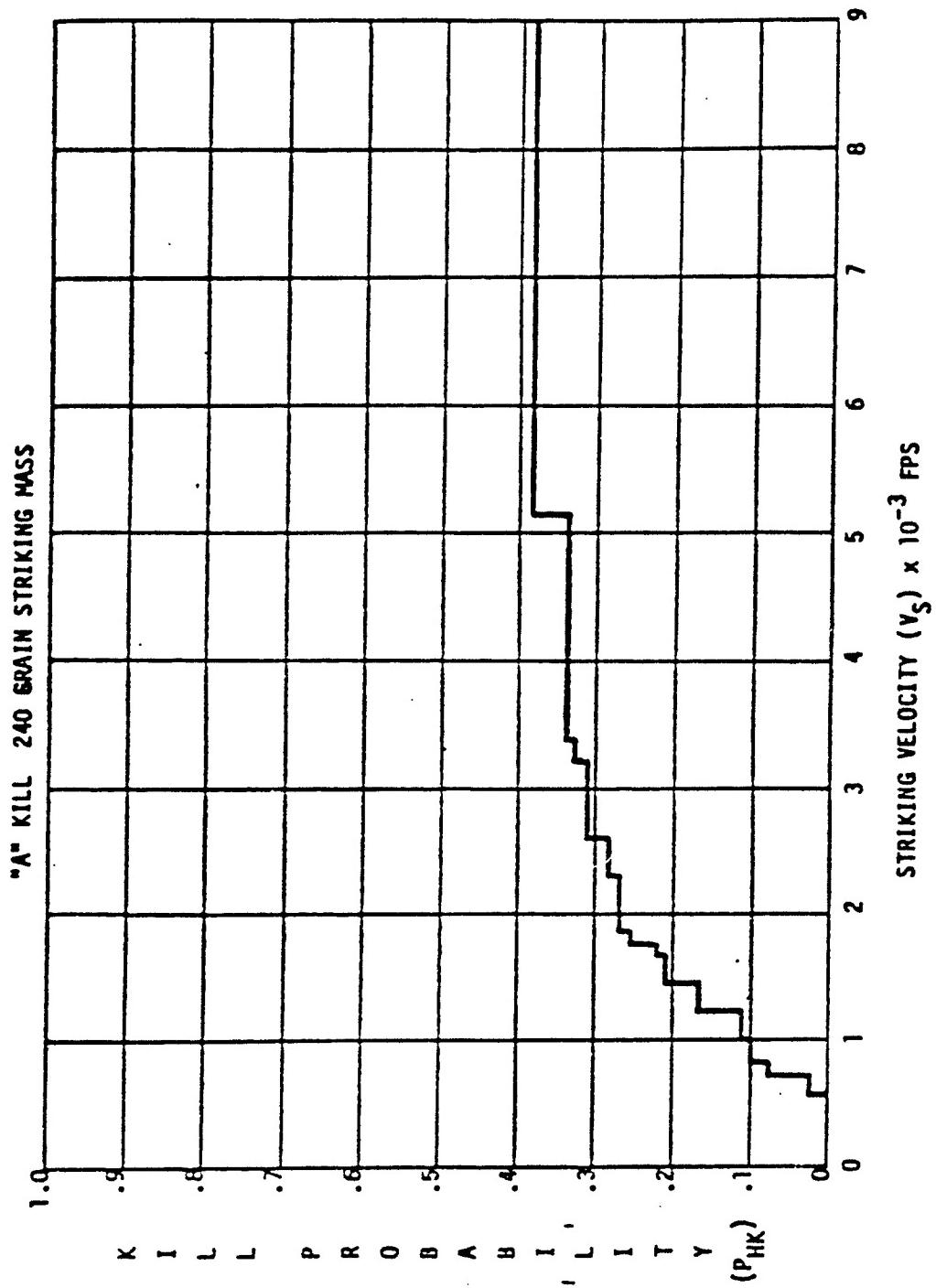


Figure A-3. Kill Probability Function for the Carburetor

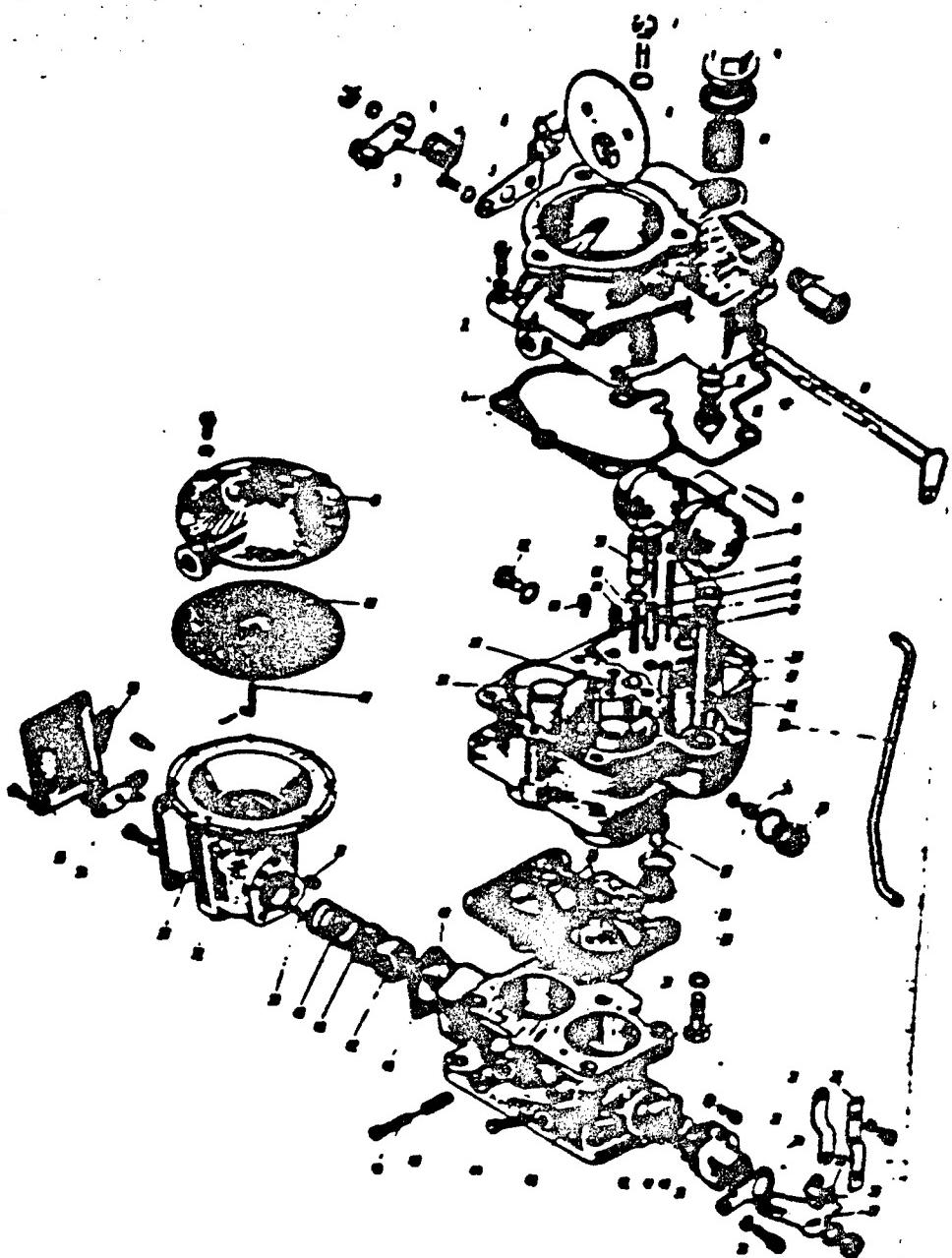


Figure 1 Exploded View of a Carburetor

DIRECT LETHALITY PHILOSOPHY

Model the fragment joint spatial and hole size distribution as a function of the total effective material line-of-sight through which the fragment passes.

EFFECTIVE LINE-OF-SIGHT FOR SPACED PLATES

$$l_i = t_{in} \sec \theta_i e_i f_i$$

base Assumption

$$T = \sum_{i=0}^n l_i$$

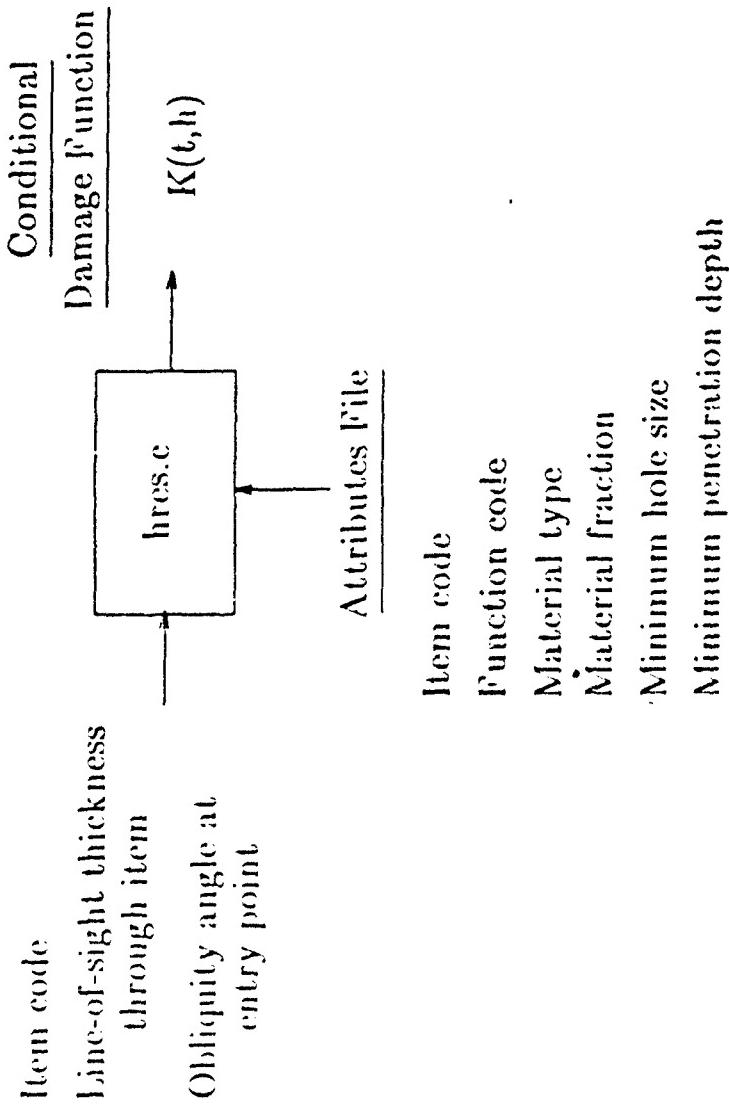
where:

- T = total effective line-of-sight
- t_{in} = normal thickness through i-th plate
- θ_i = impact obliquity
- e_i = material equivalence factor
- f_i = material fraction
- n = number of plates

MATERIAL EQUIVALENCIES

#	Code	Description	Multiplier
1	M	Steel	1.0000
2	H	Steel	1.2184
3	FH	Steel	1.1066
4		Cast Iron	0.5410
5	Al	2024	0.4607
6		Magnesium	0.3127
7		Copper	0.1548
8		Lead	0.1361
9		Titanium	0.7028
10		Tuballoy	***
11	U	Nylon	0.1448
12	B	Nylon	0.1753
	b	Brass	0.5410
	p	Plastic	0.1075
	13	Lexan	0.1075
	14	Plexiglass	0.1866
	S	Plexiglass	0.2279
	15	Doron	0.3459
	16	BR Glass	0.2465
	17	Rubber	0.0576
	18	Wood	***
	19	Water	***
	20	Cast Aluminum	0.1583
	38		

hres.c I/O



$K(t,h)$ is the probability of component kill given that the fragment can penetrate at least thickness t , can produce a hole size h at t , and encounters a critical region at t .

DIRECT LETHALITY FUNCTION

Define

$$f(\alpha, \beta; x) = \frac{\beta}{x} \left(\frac{x}{\alpha} \right)^\beta \exp \left[- \left(\frac{x}{\alpha} \right)^\beta \right]$$

Then

$$F(t | \delta, h; \epsilon) = N \exp \left[- \left(\frac{t}{\alpha_t} \right)^\beta \right] f(\alpha_\delta, \beta_\delta; \delta) f(\alpha_h, \beta_h; h),$$

where

$$\alpha_\delta = \exp (\alpha_1 + \alpha_2 t),$$

$$\beta_\delta = \beta_1 + \beta_2 t,$$

$$\alpha_h = \exp (\alpha_3 + \alpha_4 t + \alpha_5 \epsilon), \text{ and}$$

$$\beta_h = \beta_3 + \beta_4 t + \beta_5 \epsilon.$$

δ is the angle to the δ ray, and
 ϵ is the angle to the shotline.

COMPONENT PROBABILITY OF KILL

$$N_L = \int \frac{F(t|\delta, h; \epsilon) K(t, h)}{2\pi \sin\delta} dh dt d\Omega$$

$$P_K = 1 - \exp(-N_L)$$

EFFECTIVE LINE-OF-SIGHT FOR SPACED PLATES

$$t_i = t_{in} \sec \theta_i \quad e_i \quad f_i, \quad t_0 \geq t_1, \quad t_1 \geq t_2, \dots, \quad t_{n-1} \geq t_n$$

Base Assumption

$$T = \sum_{i=0}^n t_i$$

Strawman Variation

$$T = t_0 + 0.8t_1 + 0.6t_2 + 0.5 \sum_{i=3}^n t_i$$

where:

T = total effective line-of-sight

t_{in} = normal thickness through i -th plate

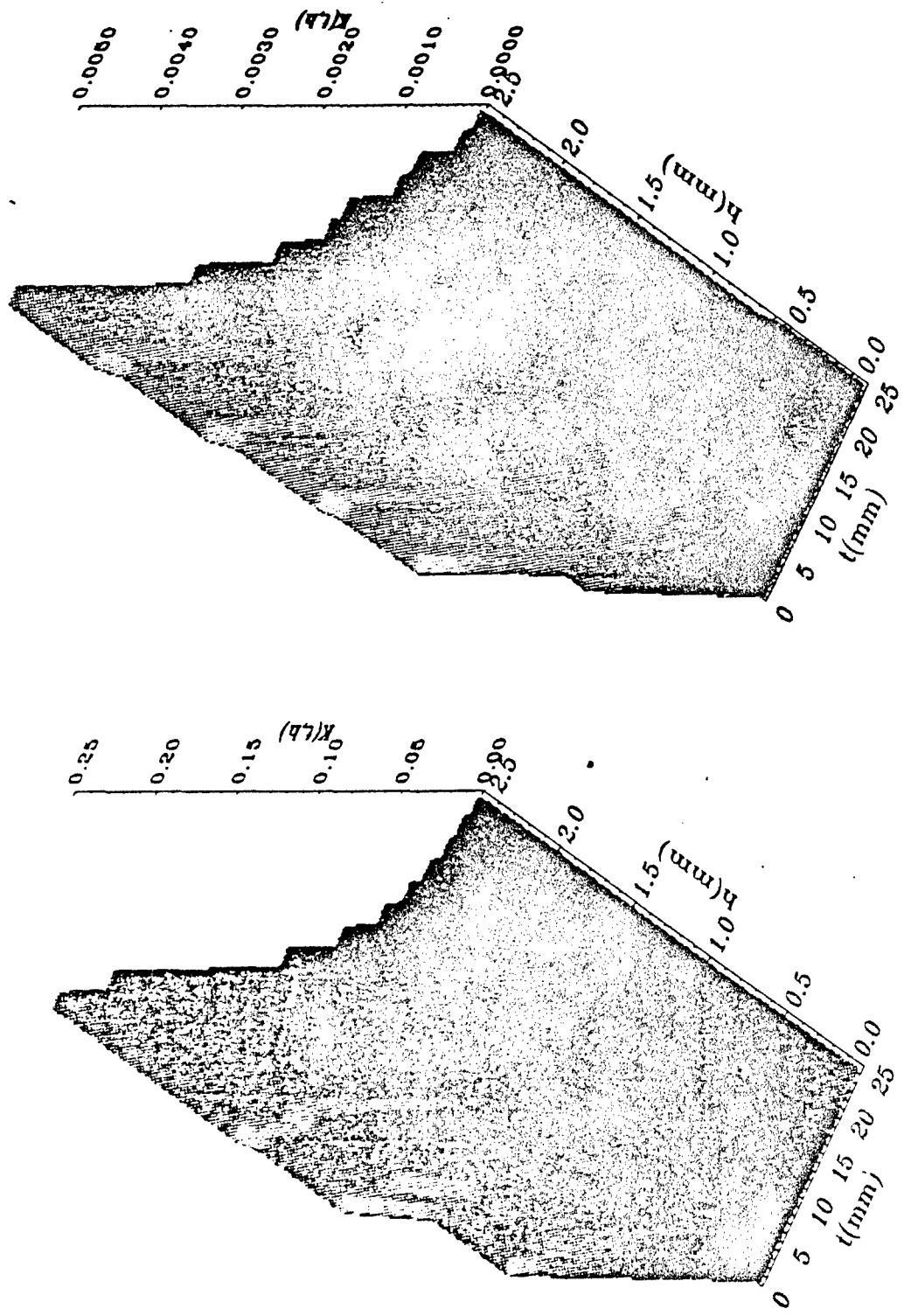
θ_i = impact obliquity

e_i = material equivalence factor

f_i = material fraction

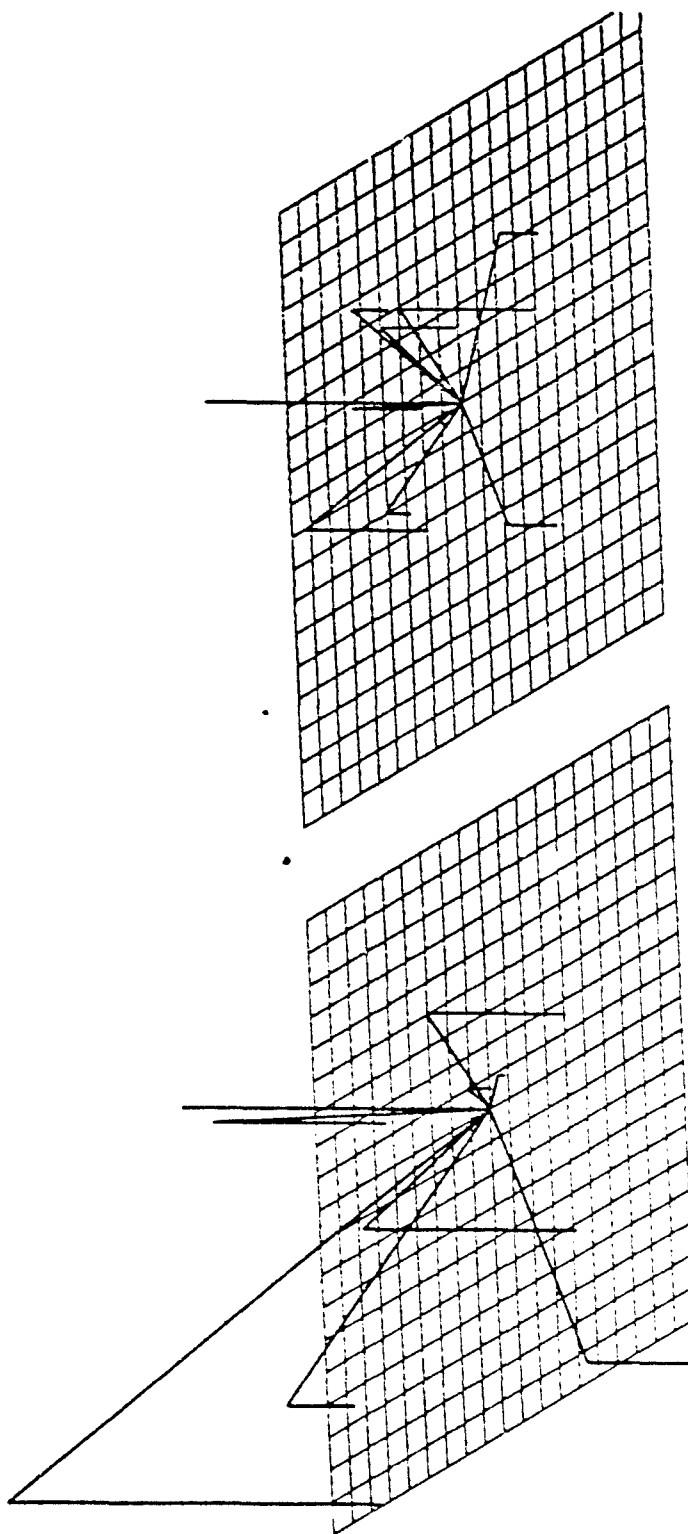
n = number of plates

Component Conditional Kill Functions



Kill Function Aspect Dependence

F0 F1



HIGH RESOLUTION COMPUTER SIMULATION OF MILITARY VEHICLE COMPONENT BATTLE DAMAGE

Robert Shnidman & Todd J. Fisher

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ABSTRACT

A critical input to detailed point-burst computer simulation models of military vehicle vulnerability is the probability of kill for critical components when they are subjected to threats produced when the armor is defeated. The primary threats considered are the residual penetrator and fragments generated during armor perforation. Until recently, the methodology of predicting component kills has lagged behind other advances in the methodology of estimating vehicle vulnerability. We have developed a computer simulation model that starts with a high resolution solid geometric model of the component. Sensitive solid regions of the component are identified. A region is considered sensitive if direct mechanical damage to the region will affect the operation of the component, or if the shock generated when the region is impacted will damage a subcomponent anywhere in the component. Raycasting techniques determine the total effective amount of material between outer surfaces of the component and the sensitive regions for a large number of attack directions and impact locations. The data thus generated is combined with the kill criterion for each sensitive region to calculate the probability of kill as a function of the hole sizes the threat produces after penetrating various amounts of material. This representation of the threat is provided by the Direct Lethality Model of the behind-armor-debris environment. Threat attack direction dependence may also be included. Different kill probabilities for the different functions of multifunctional components are considered, when needed. A final topic to be presented is functional representation of the results, so as to reduce the size of, or completely eliminate the need for, large tables as inputs to the vehicle vulnerability codes.

1. INTRODUCTION

Vulnerability/Lethality (VL) estimation of military hardware has been developed over the years to a high degree of sophistication and complexity (Deitz 1990). For ground vehicle systems, three types of analysis procedures with their corresponding computer codes exist. In order of increasing complexity, these are the Compartment, Point-Burst and Stochastic Point-Burst methodologies. Component damage estimates are needed only for the

Point-Burst methodologies. Figure 1 illustrates the data flow diagram for these methodologies highlighting the effects of the internal vehicle components.

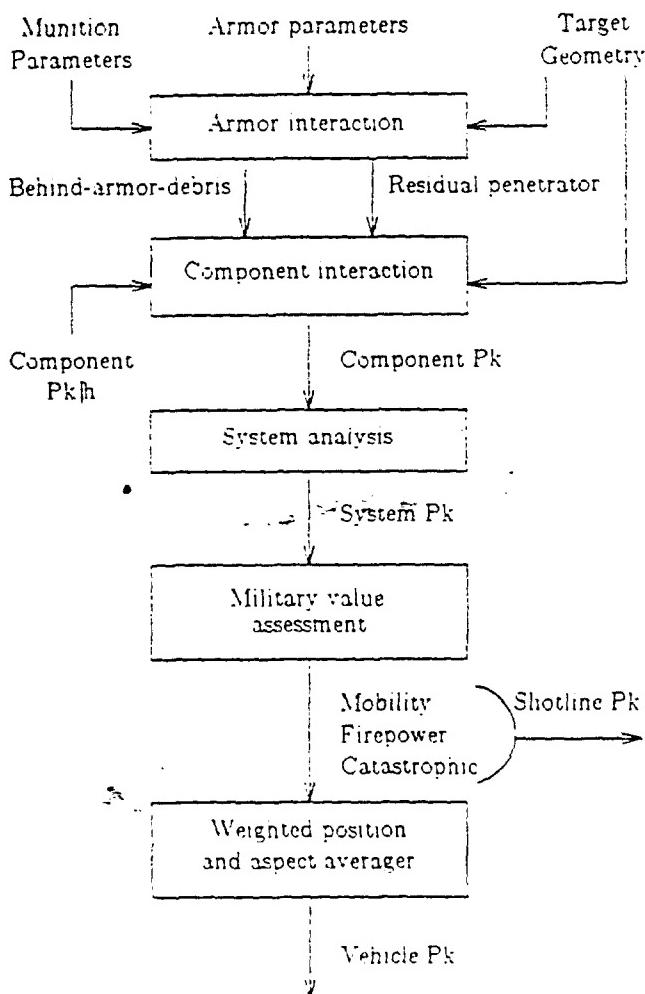


Figure 1. Ground Systems Vulnerability Assessment

As seen in the figure, munition parameters, armor parameters, and vehicle geometry are inputs to an armor interaction module that determines if the armor is perforated, and if so, predicts the state of the residual penetrator and the fragments that come from the broken armor and broken penetrator pieces. This information

together with the target geometry, material codes, and component probabilities of kill given a hit is used by the component interaction module to compute the component probabilities of kill. With the help of deactivation diagrams, this information is integrated into system kill probabilities which are then converted to loss of military value. The military loss values are then averaged over the expected vehicle hit location and munition arrival direction. As can be seen, a critical link in the VL estimation process is the determination of the kill probability of critical components when hit by the residual penetrators and by fragments generated when the armor is defeated.

II. PREVIOUS METHODOLOGY

The previous methodology for estimating component kill probabilities (Kruse and Brizzolara 1971) was conceived two decades ago and has had only minor revisions and extensions over its lifetime. Briefly, this methodology consists of the following. Each component is modeled as a six sided box. To each face of the box is assigned a presented area and one or more instances of the following set: 1) a sensitive area, 2) a minimum hole size, and 3) a list of barrier thicknesses required to be perforated in order to reach the sensitive area along with a material type identifier for each barrier. Each face is then sampled from five directions: normal to the face and four directions at 45 degrees, from the normal - up, down, right, and left. Along each direction for selected combinations of mass and speeds, THOR penetration equations (Ballistic Research Laboratories 1961) are used to determine if the fragment is capable of reaching the sensitive region and producing in it at least the minimum hole size. If these two conditions are met, the ratio of the corresponding sensitive area to presented area is calculated. These ratios are summed over each face and averaged over all of the faces. The probability of component kill is taken to be equal to this average. A technique for correcting the sensitive area for the finite size of the fragment is given in the reference.

This methodology has several shortcomings. The first is that a six sided box is a crude model for most components. The second is that only a small number of fragment directions are sampled and even these are not optimal. The third major shortcoming is the use of a penetration prediction methodology that uses an average fragment shape factor. The shape factor, λ , is defined by

$$A = \lambda m^{2/3} \quad (1)$$

where A is the average fragment presented area, averaged over all fragments and orientations, and m is the fragment mass. Since the vulnerability modeling is highly nonlinear, averaging variables too early in the calculations leads to inaccuracies in the results.

III. INPUTS TO THE HIGH RESOLUTION MODEL

The High Resolution Component Kill Methodology is based on a detailed high resolution geometric description

of the component together with ballistic resistance characteristics and vulnerability information on the internal parts of the component. Extensive sampling is performed on the geometric model, and the form of the sampling results are designed to smoothly mate with the most current detailed probability density description of the fragment threat. In the remainder of this section we present the inputs to the High Resolution Model and the tools which aid in their preparation. The following section will describe the form of the current threat description, and the subsequent section will show how the component probabilities of dysfunction in the vehicle are calculated.

A. Geometric Modeling

At the heart of the current methodology are the tools required to produce accurate and detailed analytical solid geometric models of components. The BRL-CAD package (Muuss 1988) is, with its MGED solid modeler, the tool of choice for our purpose. The MGED modeler is primarily a combinatorial geometric modeler. That is, it builds geometric objects with boolean operations on basic geometric primitives. The geometric primitives are called solids, and the boolean combinations of solids are called regions. A region represents the smallest piece of actual geometry and is considered to be homogeneous. Each region can be assigned its own identification code. Regions can be grouped into a hierarchical structure of groups, and each group has an associated rotation-translation-perspective-scaling matrix. Regions can also be instanced so that future changes to the region will automatically be reflected in all the instances of that region. Construction of models is performed on a color graphics workstation using a highly interactive user interface. Figure 2 is a transparent black and white rendering of a vehicle component model built with MGED.

B. Geometric Interrogation Software

The MGED modeler produces a file containing solid parameters, the boolean rules for forming regions, and the group structures and their matrices. However, in order for applications to use the geometry, the proper geometrical information must be extracted in the required format. This is accomplished with the model interrogation software that consists of the ray-tracing (RT) library in the BRL-CAD package. Ray-tracing consists of solving for the intersection points of lines with the region boundaries. At these intersection points, surface normals and curvatures may be calculated if needed.

A convenient code that allows easy interface to the RT library is called RIP (Moss 1988). Among the inputs to RIP that one can specify either on the command line or interactively are: the identification codes for critical regions (the regions for which the intersections of rays should be calculated), either single ray firing coordinates and directions or the specification of a grid of rays, and input and output file names. A convenient output format is provided by RIP. An output of particular interest for our purpose is the length of the line segments through the

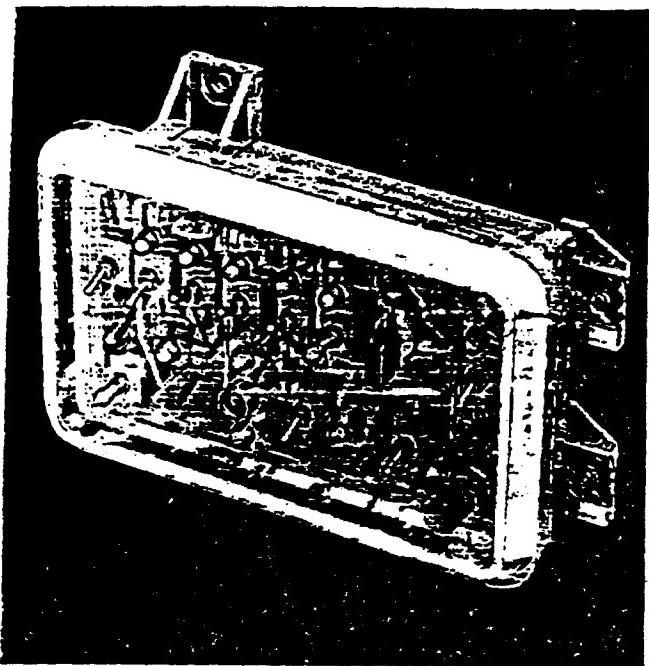


Figure 2. Drivers Master Panel

critical regions or groups that form the critical subcomponents along with the identification codes of these regions.

C. Sampling on a Sphere

Since the threats to components can come from any direction in space, we need a means for sampling from arbitrary directions. Two approaches are possible: uniform sampling or random sampling. Since there does not exist a regular polyhedra with more than twenty vertices, it is impossible to uniformly sample a sphere at more than twenty points. If more points are desired, then one must settle for pseudo-uniform sampling. An algorithm that we have used is as follows (Hanes 1991). The sphere is divided into polar angle bands of equal width and the number of samples in each band is proportional to the sine of the polar angle of the band. The samples are uniform in azimuth for each band, however, the starting azimuth for each band is chosen randomly.

If completely random sampling on a sphere is desired the following algorithm may be employed. The arc cosine of a uniform random number from one to minus one should be taken for the polar angle, and a uniform random number from zero to 2π should be taken for the azimuthal angle.

Given the results we obtain with the sample directions, several alternatives are possible. One is simply to uniformly average over all the sampled directions. Another possibility is to perform a weighted average dependent on the expected attack distribution. And a final possibility is to retain the directional dependence and interpolate or fit a function to the directional dependence

and have the vehicle vulnerability code pick the result for the exact directions as needed.

D. Attributes File

In addition to the geometric description of the component, other attributes of the component's subcomponents must be specified. These attributes are related to the ballistic equivalence of the subcomponents and to the vulnerability criteria of the critical subcomponents. Specifically, for each subcomponent the following attributes are provided:

- a material type code,
- a material fraction; that is, what fraction of the subcomponent is not air,
- a minimum hole size a fragment must produce and a minimum distance in the subcomponent that the fragment must penetrate to render the subcomponent nonfunctional, and
- for which function or functions of the component the subcomponent is critical.

We will see how all of this information is used to compute the probability of component nonfunctionality after we present in the next section the description form of the threat fragment cloud.

IV. DIRECT FRAGMENT LETHALITY

A. Modeling Variables

The modeling of the fragment cloud produced when armor is defeated by a penetrator is currently performed in a semi-empirical way. The number of variables required for a complete description of the cloud is rather large, and data-on-all of these variables is difficult if not impossible to come by. One must then chose variables that accurately describe the phenomena for the desired purpose and for which good data can be obtained. Previous practice was to use the fragment mass and velocity and an average shape factor as given in Equation (1) as the description variables. The drawback of using average shape factors was discussed above, and difficulties of using mass and velocity are related to the way the data is collected.

The current fragment data collection technique is to place several thin metallic sheets, referred to as witness plates, behind the armor and then measure the locations and sizes of the holes produced in these plates. Fragment masses can be estimated from the sizes of the holes using the average shape factor. However, since the exact fragment shape and impact orientation is unknown, the error in determination of the mass is rather large. Given a mass estimate, an estimate of speed can be made from the number of plates perforated. For the speed the uncertainty of the determination is even greater than for the mass. For these reasons a different set of variables and description scheme was sought.

Since the primary kill mechanism for most components is penetration into sensitive regions, the present method utilizes variables directly related to penetration and are general enough to be of value for other damage mechanisms. These variables are hole size and depth of penetration. It is significant and important to understand that the way we model with these variables is to model the hole size distribution that would be produced as a function of penetration depth. That is, we do not attempt to model how deeply a fragment penetrates but rather we model the distribution of holes sizes produced at a given depth by fragments that penetrate at least this distance. The reason for this modeling approach is that it describes exactly what is observed on the witness plates. On the witness plates we observe holes at given perforation depths and have no way to accurately infer how deep a fragment that produced a given set of holes in the plates could penetrate. Moreover, this approach relates well to the damage mechanism of producing holes in sensitive regions; i.e., at given depths of penetration.

B. Simplifying Assumptions

1. Penetration as a Function of Effective Line-of-Sight

A major assumption presently used in the Direct-Lethality Model is that the penetration process can be modeled based on the total line-of-sight of material. Equivalency factors are used to relate perforation in different materials. With this assumption, the detailed configuration of the matter to be penetrated is neglected. That is, we assume in the model that perforation of one piece of matter or several pieces of matter of the same total thickness is identical. At very high velocities and for small fragments, this assumption has limited accuracy for widely separated plates due to the phenomenon of fragment breakup. With slower or more massive fragments, we have shown that the equivalent line-of-sight assumption is a good approximation. For most of the lethal fragments in the behind-armor cloud, the present assumption appears reasonable.

2. Fragment Hole Sizes as a Function of Effective Line-of-Sight

Another major assumption presently used is that the distribution of hole sizes produced by the fragment cloud is a function of the effective line-of-sight and independent of the detailed configuration of the penetrated matter. For small fragments traveling at extremely high speeds this assumption has limited accuracy, especially when relating hard materials with soft ones.

3. Symmetry of the Fragment Spatial Distribution

At present we assume that the number density of the fragments is circularly symmetric about some axis in space. For normal munition incidence on homogeneous armor this assumption can be rigorously justified. This assumption loses accuracy in some cases when the munition attack obliquity angle approaches high values. Nevertheless, for the most part this assumption has been found to be adequate. This particular assumption is not crucial for the Direct Lethality Model but is made for the

sake of convenience. It could be relaxed when a suitable means for doing so is found.

All of the assumptions of the Direct Lethality Model are now under scrutiny at the BRL and in the international arena.

C. The Form of the Direct Lethality Model

The Direct Lethality Model has been documented (Shnidman 1988a & 1988b). Here we recap the model. The density function is defined as follows. First we define the Weibull probability density function of variable z with scale parameter α and shape parameter β

$$f(\alpha, \beta, z) = \frac{\beta}{z} \left(\frac{z}{\alpha} \right)^{\beta-1} \exp \left[- \left(\frac{z}{\alpha} \right)^{\beta} \right]. \quad (2)$$

The Direct Lethality density function can then be written as:

$$F(t | \delta, h, \epsilon) = N \exp \left[- \left(\frac{t}{\alpha_0} \right)^{\beta_0} \right] f(\alpha_0, \beta_0, \delta) f(\alpha_1, \beta_1, h) \quad (3)$$

where

$$\alpha_0 = \exp \left(\alpha_3 + \alpha_4 t \right) \quad (4)$$

$$\beta_0 = \beta_1 + \beta_2 t. \quad (5)$$

$$\alpha_1 = \exp \left(\alpha_5 + \alpha_6 t + \alpha_7 \epsilon \right), \text{ and} \quad (6)$$

$$\beta_1 = \beta_3 + \beta_4 t + \beta_5 \epsilon. \quad (7)$$

t is the effective line of sight thickness, δ is the angle that a fragment trajectory makes with the average trajectory of the fragments, ϵ is the angle a fragment makes with the shotline, and h is the fragment's induced hole size. There are 13 free parameters in this model. They are N , α_0 , β_0 , α_1 through α_5 , and β_1 through β_5 . In practice we transform the first two parameters to two other ones that show better shot to shot behavior. These new parameters are the number of holes that would be made in a plate of a given reference line-of-sight thickness and the ratio of the number of holes that would be made in two plates of different reference cumulative line-of-sight thicknesses. This density function gives the expected number of fragments in the intervals $[\delta, \delta + d\delta]$ and $[h, h + dh]$ at given values of t and ϵ . The parameters are determined from data gathered after controlled test shots. A maximum likelihood technique determines the most likely value of the parameters consistent with the data. Having so obtained the parameters for the conditions of each shot, the parameters themselves are modeled as a function of the munition-target conditions thereby providing a Global model of the debris cloud that will predict its properties over a range of interaction conditions: such as, target type, composition, and thickness, impact obliquity, munition size and velocity and so on.

V. COMPONENT CONDITIONAL KILL

Given the inputs described in Section III, we compute the component condition kill, $P_{K|H}$, for each sampling ray. $P_{K|H}$ is the probability of kill given a hit on the component.

A. Kill Functions

The results for arbitrary averages; e. g., over hit location and/or attack aspect, require the construction of functions from the individual ray results. We first present the analytic form of these functions and show how they mate with the Direct Lethality function, and then describe a procedure for numerically building the functions from the single ray values.

The first function needed is a function $p(t)$ that is the probability a total effective material thickness t needs to be penetrated to reach any sensitive region of any critical subcomponent. We require $p(t)$ to be normalized, that is,

$$\int_0^{\infty} p(t) dt = 1. \quad (8)$$

For simplicity of the presentation, we assume simple averages over all hit locations and attack aspects, thus $p(t)$ is shown without an aspect dependence.

The second function needed is a function $k(t, h)$ that is the probability of component kill given that the fragment can penetrate at least thickness t and can produce a hole size h at that value of t and given that there is a critical subcomponent at the depth of penetration t . It then follows that the average number of lethal hits on the component is given by

$$N_L = \int \frac{F(t | \delta h | \epsilon) p(t) k(t, h)}{2 \pi \sin \theta} dh dt / \Omega \quad (9)$$

where F is given in Equation (3) and Ω is the solid angle of the component subtended from the source of the fragments. The probability of component kill (P_K) is equal to the probability of the component being hit by one or more lethal fragments. Assuming a Poisson distribution of lethal hits, the component P_K is then given by

$$P_K = 1 - \exp(-N_L) \quad (10)$$

B. Numerical Construction of the Kill Functions

A conceptually simple approach to the construction of the kill functions starts with binning the variables t and h . That is, a number of values of t and h are chosen, and whenever t to a critical region is between two of the chosen values for a ray, the corresponding bin for $p(t)$ is incremented by unity. Likewise, whenever both t and h are between two of their chosen values respectively, the corresponding two-dimensional bin is incremented by the ray value of k . The p bin values are then divided by the total number of rays cast to obtain the proper averages. Similarly, the k bin values are divided by the corresponding p bin values. The integral in Equation (9) is then performed by summing the integrand over all of

the bins. The only significant computational burden of this approach for the generation of the p and the k functions is the storage requirement for all of the bin values for all the functions of all the critical components. For example, if we have 25 bins each for t and h and the sum of functions for the critical components is 400, then a total storage of about 250K words is required. This is not a small amount of computer memory, but it can easily be handled with existing hardware. Major computational power is, however, required for the vehicle vulnerability code that uses the p and k functions since the integral in Equation (9) must be evaluated in the innermost loop of the code. This loop must process each spall ray from each sample munition hit point on the vehicle and the number of such spall rays can approach the tens of millions.

C. Functional Representation

Work is proceeding to fit the numerically calculated p and k functions to analytical functions in order to simplify their use and reduce data storage requirements. At this point, it is too early to make definitive statements. However, based on very limited results for real components, it appears that at least the p function can be represented as a constant times a power of t .

VI. SUMMARY & CONCLUSIONS

In this paper we have briefly outlined the data flow for vehicle vulnerability assessment and shown where the effects of component damage estimation enter. Previous techniques for estimating component dysfunction probabilities and the limitation of these techniques were discussed. Advances in analytical solid geometric modeling that form the basis of the High Resolution simulation of component damage were presented along with an outline of the software that interfaces to the geometric models and extracts information therefrom. The Direct Lethality description of the threat fragment cloud and its assumptions has been described in sufficient detail to understand how this description is used in the context of the High Resolution damage model. Two component kill functions were defined, and an example given on how to calculate them from the geometric and subcomponent attribute information. The integration over these kill functions multiplied by the threat fragment density function then leads to the estimate of the component probability of kill.

To date we have implemented a bare bones concept demonstrator code to calculate the two component kill functions and have applied this code to both a simple test case and to real components. The results appear to be reasonable and consistent. In the near future routines will be added to current vehicle vulnerability estimation codes to utilize these functions. Additional refinements to the concept demonstrator code which correct for the finite fragment size are presently being designed.

We are very pleased that the major improvement in estimating component battle damage described herein has been formulated and implemented and look forward to

seeing this methodology used to provide more accurate, reliable, and credible vehicle vulnerability estimates.

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Appendix D

Abstract for PKGEN Report

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MEMORANDUM REPORT BRL-MR-DRAFT

**COMPUTER-AIDED METHODOLOGY FOR GENERATING
COMPONENT PROBABILITY OF KILL FUNCTIONS**

JAMES E. HUNT

APRIL 1992

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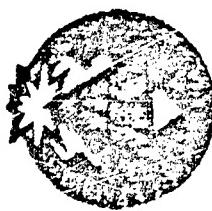
Abstract

Component probability of kill given a hit ($P_{K/H}$) functions are crucial inputs for component level vulnerability codes. Traditionally, $P_{K/H}$ functions were developed both empirically using test data and analytically, either by hand or utilizing a simplified computer model. Most often, developing $P_{K/H}$ functions for a particular vulnerability analysis consisted of searching similar past analyses to find acceptable existing component $P_{K/H}$ functions.

To aid the analyst in $P_{K/H}$ generation, and to attempt to standardize the process, the component probability of kill given a hit function generator (PKGGEN) program either *quantitatively* interrogates existing components in a combinational solid geometry (CSG) database utilizing raytracing techniques, or prompts the analyst for a *qualitative* description of the component. In both cases, defeat criteria for sensitive areas of the component are supplied as a function of the residual ballistic penetrator. These defeat criteria are typically penetrator mass, velocity, hole size, surface area, residual penetrating ability, material removal capability, etc. Once geometric and criticality information are supplied, PKGEN either collects threshold killing velocity datapoints for various penetrator striking masses or measures the hole sizes and equivalent depth of penetration into steel needed to effect a kill. This data is used to generate a basic component $P_{K/H}$ function useable by component-level vulnerability models. A graphics window editor allows an analyst to interactively display and/or edit these functions to better fit the data as necessary.

Appendix E
Briefing Package: LTTB

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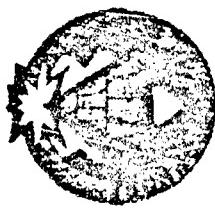


LTTB Component P_{KH} Requirements

US Army
Laboratory Command

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- Input to fragmenting munition and direct-fire analyses.
 - VAST, SPRAE
 - Probability of Kill as a function of fragment mass and velocity.
- $P_{KH}(m,v)$
 - Step functions or curve fit equations.
- Current and future need for P_{KH} due to behind armor debris.
 - Currently map spall into fragment mass/velocity distributions.
- Consistent, reproducible, efficient, timely, cost-effective, accurate methodology

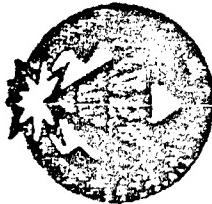


PKGEN

BALLISTIC RESEARCH LABORATORY

US Army
Laboratory Command

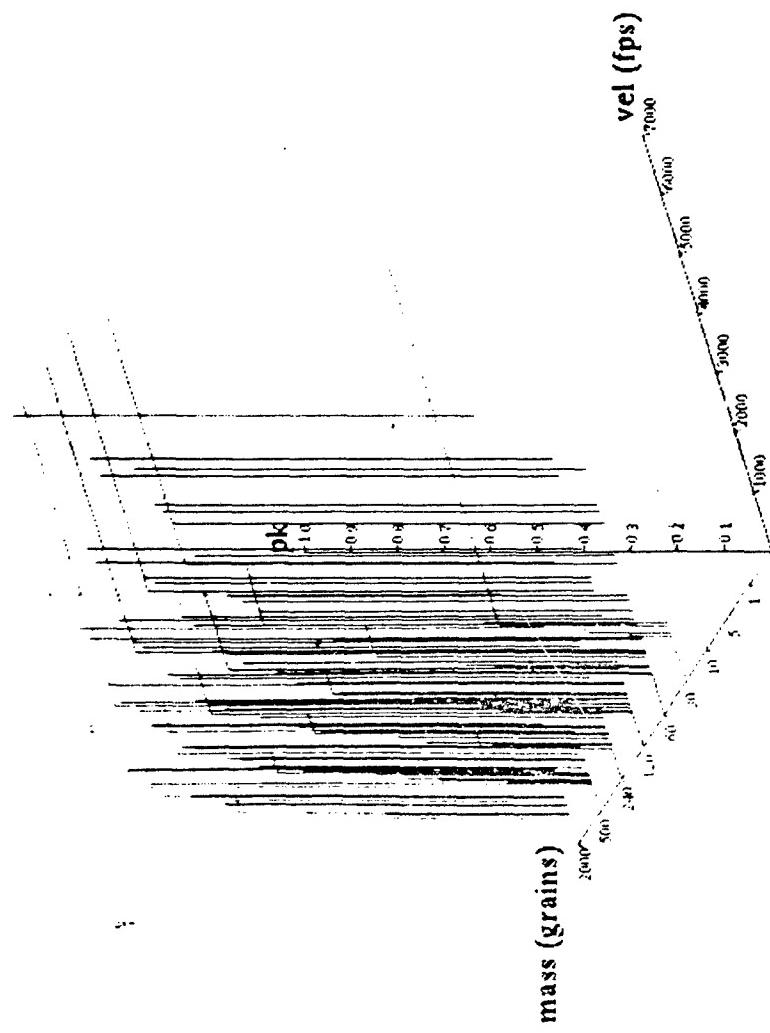
- Computer-Aided Generator for Component Conditional Probability of Kill Functions
- Uses BRLCAD rt library to interrogate geometric components
- Uses THOR penetration algorithms and user-defined defeat criteria
- Can also interrogate a qualitative description of component when no geometry exists
- Collects threshold velocity datapoints for various fragment striking masses
- Estimates step functions from quantitative or qualitative data set
- Supplies a graphics window editor for interactive editing by an analyst
- Self documents generated functions in a step function library

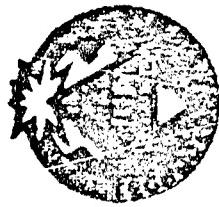


PKGEN -- Step Function for all Masses

US Army
Laboratory Command

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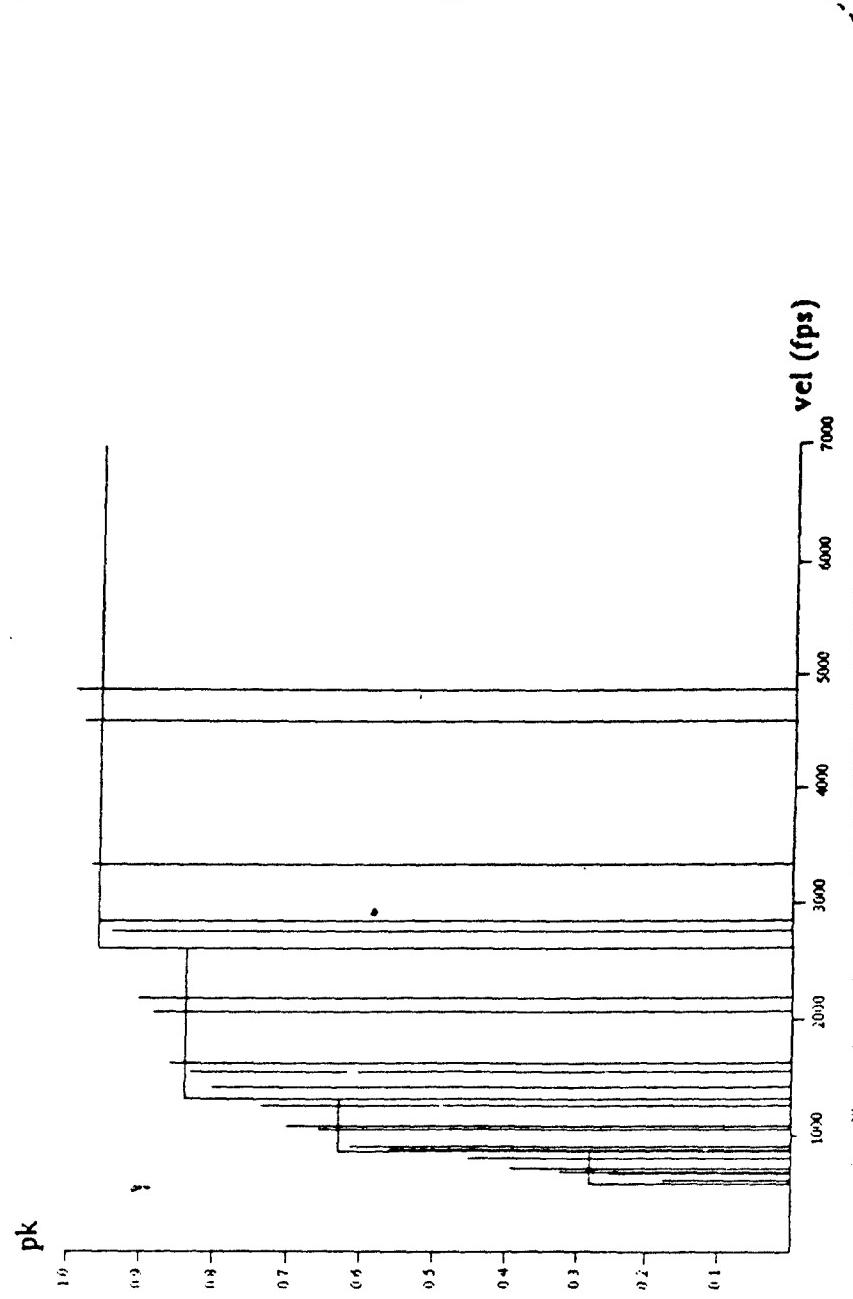


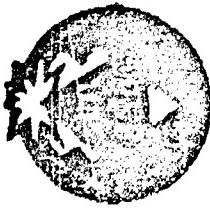
PKGEN -- Step Function for a Single Mass

US Army
Ballistic Research Laboratory

US Army
Laboratory Command

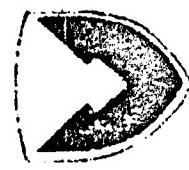
mass = 120 grains





PKGEN Function Documentation

BALLISTIC RESEARCH LABORATORY



US Army
Laboratory Command

BRL-CAD Release 3.31 PKGEN Version 2.9
Mon Nov 18 13:08:41 EST 1991, Compilation 6
jehunt@voice.brl.mil:/usr/local/vld/jehunt/cad/.pkgen.4d

Component PK/H Documentation on Sat Feb 8 08:38 1392

ANALYSIS: Qualitative

UNITS: english

INPUTS: shape = C (cylinder)

diameter = 0.3 mm

layers = 1
Layer #1: material two = 1

thickness = 0.1

interior material type = 1

percent sensitive interior

depth = Hole 0.01 & Depth 0.02

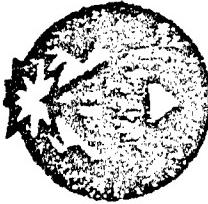
תְּרֵי גָּמָם = ۳۰:۶

MASSES:

1-0

Step function estimation: (CONSERVE = Averaging)

Four step function "linkage":



PKGEN Function Documentation

BALISTIC RESEARCH LABORATORY

US Army
Ballistic Comd

BRL-CAD Release 3.31 PKGEN Version 2.9
Mon Nov 13 13:03:41 EST 1991, Compilation 6
jehunt@voice.brl.mil:/usr/local/vld/jehunt/cad/.pkgen.4d

Component PK/H Documentation on Thu Feb 20 16:51 1992

ANALYSIS: Quantitative.

UNITS: english

REGIONS:

8500 0 1 100 { Barrier } /motor/r.d3
8511 0 1 30 { ** } /motor/r.d3.1
{ ** v 100 & h .1 }

PARAMETERS: (are default unless noted below:)

CELLSIZE = 0.25 in

FRAGSHAPE = 0.01306

PENET = STEEL

MASSES:
1.0 5.0 10.0 30.0 60.0 120.0 240.0 500.0
2000.0

Step function estimation: (CONSERVE = Averaging)

Two step function "motor":

0	0	0	0	0	0	0	5600	28	6400	35	motor					
4400	25	5700	48	3400	29	5200	55	2700	36	4900	62	2100	44	4600	67	motor
1300	54	4200	73													

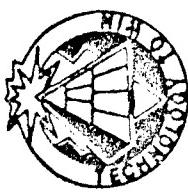
Step function after modification:

Two step function "motor":	0	0	0	0	0	0	5600	28	6400	35	motor
0	0	0	0	0	0	0					

Appendix F

Briefing Package: IBAB

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Component P(k/h) & P(I/H) - TQM Workshop

26 March 1992

Sheraton Inn, Aberdeen, MD

US ARMY
LABORATORY COMMAND

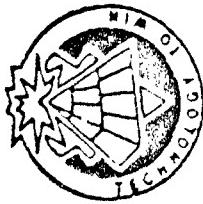
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PERSONNEL

VULNERABILITY / SURVIVABILITY

ASSESSMENT

Edward G. Davis
U.S Army Ballistic Research Laboratory
Aberdeen Proving Ground, Maryland



Vulnerability/Lethality Division

US ARMY
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Ground Systems Branch

- Vulnerability of armored combat vehicle
- Lethality of anti-armor munitions
- Inputs to Army studies; COEAS & ROCS

Systems Assessment Branch

- Live Fire Testing/Assessment
- Joint Live Fire - Ground Systems
- Vulnerability reduction -Ground Systems

Air Systems Branch

- Vulnerability of air targets
- Vulnerability reduction - air systems
- Joint Live Fire - Air Systems

Vulnerability Methodology Branch

- Geometric & Material modeling
- Target Signatures
- Advanced Computer Technology

Logistical/Tactical Targets Branch

- Vulnerability of Air Defense Systems
- Spare parts requirements predictions (SPARC)
- Lethality of Artillery Munitions

Integrated Battlefield Assessment Branch

- Analysis of unit level operations
- Vulnerability of personnel
- Chemical and nuclear matters

PVT Mission

Personnel Vulnerability (formerly Wound Ballistics) Mission for AMC:

- Provide data & models on antipersonnel effects of fragments, bullets, flechettes, blast & thermal mechanisms for munition effectiveness.
- Casualty assessment for LFT, other DOD programs
- Develop models, incap. criteria, new methodology
- In-house & customer SA bullet evaluations (e.g., FBI, Secret Service)
- In-house and customer ballistic studies on body armor & helmet materials (e.g., NRDEC)

PVT Areas

Experimental - Peep Site Range

- Testing of Body Armor Materials
- Lethality Assessments of SA Ammo
- Misc Ballistic Testing (M1 comp, SS,...)

Analytical

- Wound Ballistics Modeling
 - Computer Man
 - Casualty Criteria
- Casualty Assessment (e.g. LFT, SAE, HIP)
 - Assessment of Field Data
 - Methodology Development

PVT INTERACTIONS

CUSTOMER & CONSULTATION

Army Agencies

AMSAA, NRDEC, MTL, NVEOL, HEL,
TECOM, AMC Field Safety Office,
Med R&D Command, LAIR, WRAIR,
USAFAS, JTCC, CRDEC, ARDEC
LANL, LLNL

National Labs Universities

USUHS, U. of Tenn, U. of Ala,
Academy of Health Sciences, OSU

Project Managers Contractors

HIP, BFV, Abrams
IDA, Service, Analytics, SWRI,
Medianatic Res, ASI, QSI, BDM,
Mc Donnel-Douglas, JAYCOR, T&E
Int, Tri-Analytics, Allied Chem
CDE, ETAS, DRET, PR China
PA State Police Crime Lab, MD
State Police, Harford County
Sheriff's Dept.

Foreign Local Government

FBI, Secret Service, DDESB,
NBS, U.S. Consumer Protection
Agency, CIA, NWC, NWSC, CID,
FSTC, David Taylor Research
Center, SMO, Special Operations
Forces, U.S. Customs Service,
Navy SEALS

Miscellaneous

Levels of Casualty Analysis

A. Weapon-Environment Level

- **Weapon Characteristics**
- **Initial Conditions**
- **Hit Probability**

B. Individual Level - Given a Hit

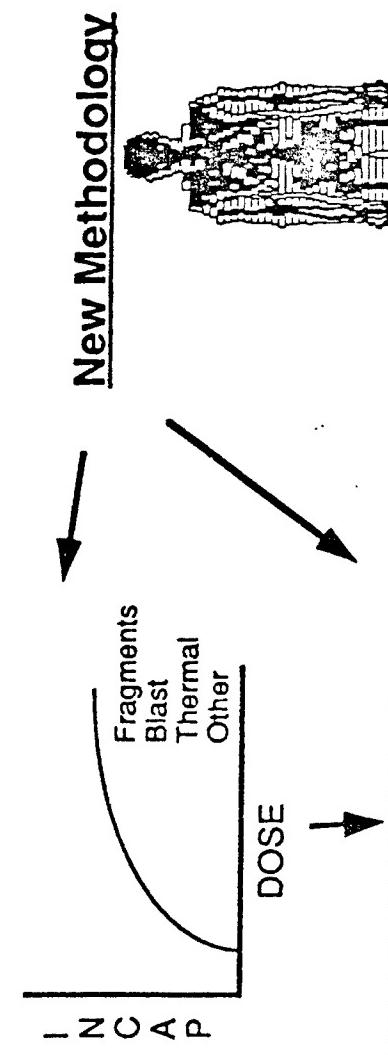
- **Injury Assessment**
- **Incapacitation Assessment**

Personnel Vulnerability

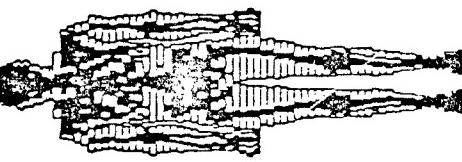
Data & Models

Testing

- Bullet Lethality
(Gelatin Studies)
- Personnel Armor
Effectiveness



New Methodology



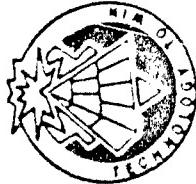
Casualty Assessment

JMEM's
V/L CODES
LFT

ComputerMan

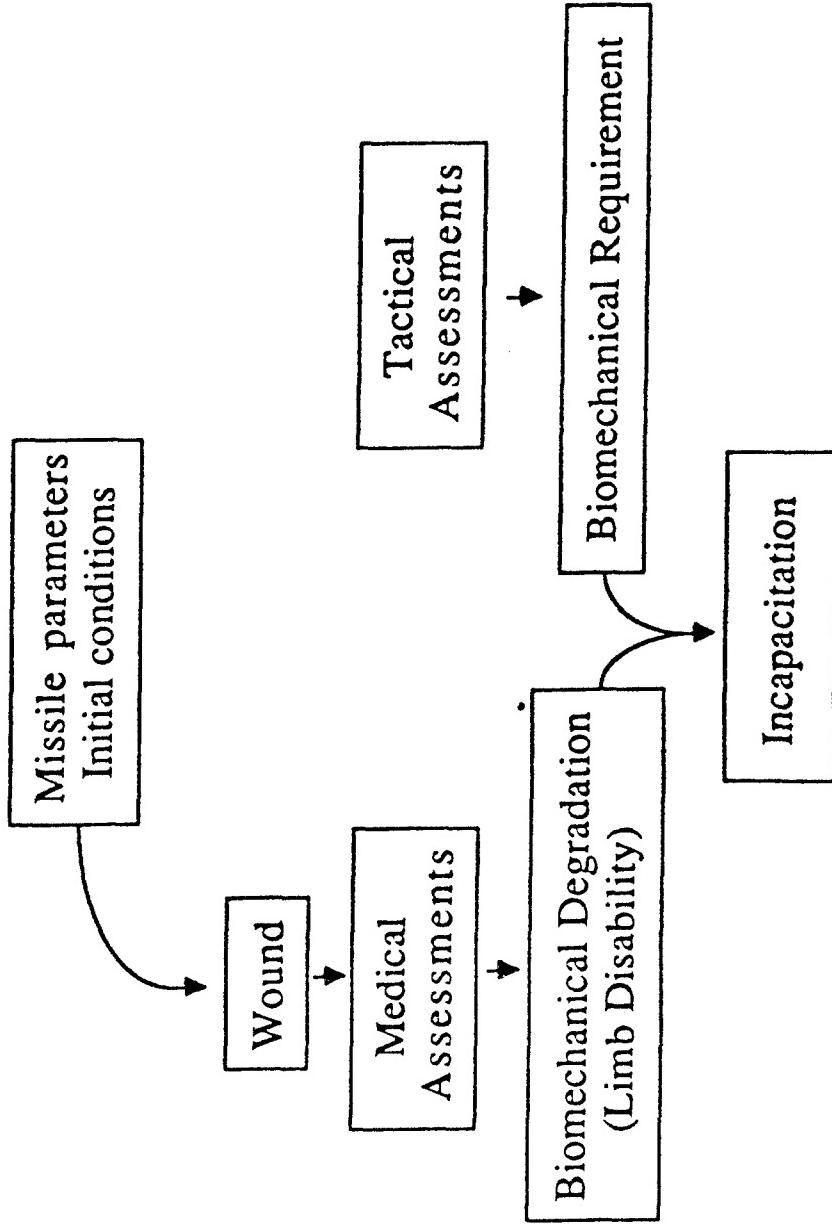
- Multiple Wound Studies
- Wound Tract Analysis
- Crew Casualty Program

⋮



General Incapacitation Model

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BALLISTIC RESEARCH LABORATORY



A WORD ABOUT TERMINOLOGY

INCAPACITATION:

The partial or complete inability to perform the physical tasks required of a particular combat role.
(Incapacitation implies some specific requirement)

CASUALTY:

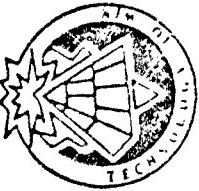
An incapacitated individual.

- ✓ may require medical attention
- ✓ may be a fatality

P(I//H):

"Probability of Incapacitation, given a Hit": An expected value loss of function, i.e. $P(I/H) = .40$ (40% incapacitated). Expressed as a function of (ballistic) dose, time & role.

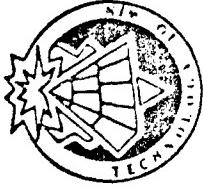
Casualty Producing Damage Mechanisms



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- KE Wounding
- Blast Overpressure
- Thermal
- Toxic Gases
- Acceleration



Kinetic Energy Wounding

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LABORATORY COMMAND

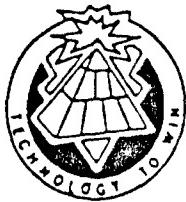
- Armor Fragments, Residual Penetrator
- Most common, most severe AFV injury

Instrumentation

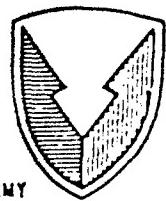
- Ballistic Manikin
- CVC Clothing/Equipment

Data Evaluation

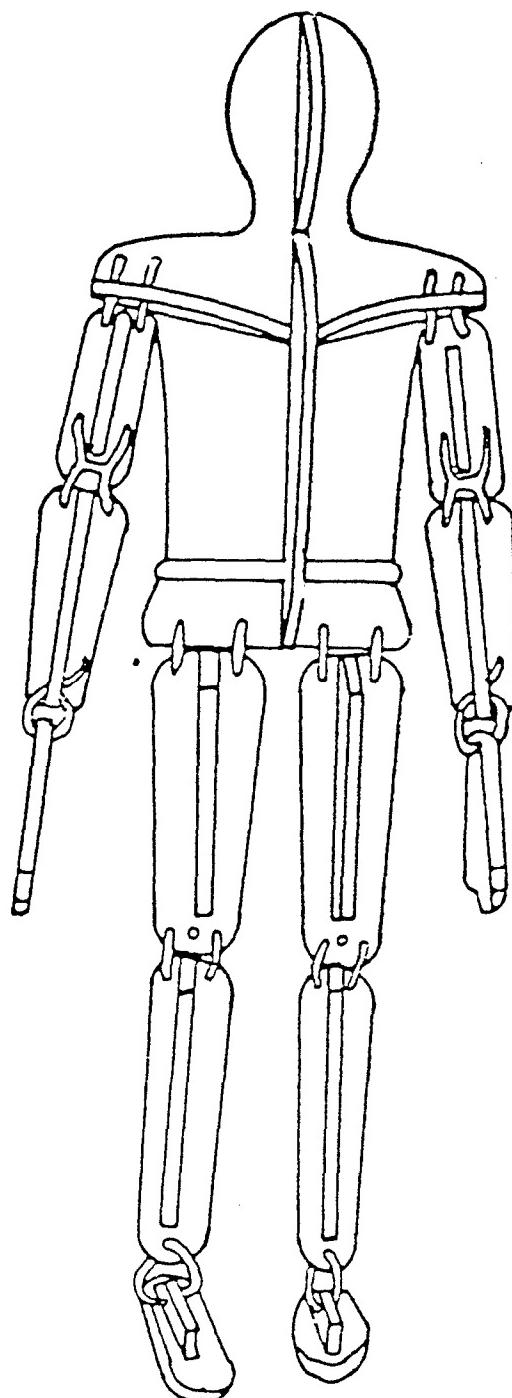
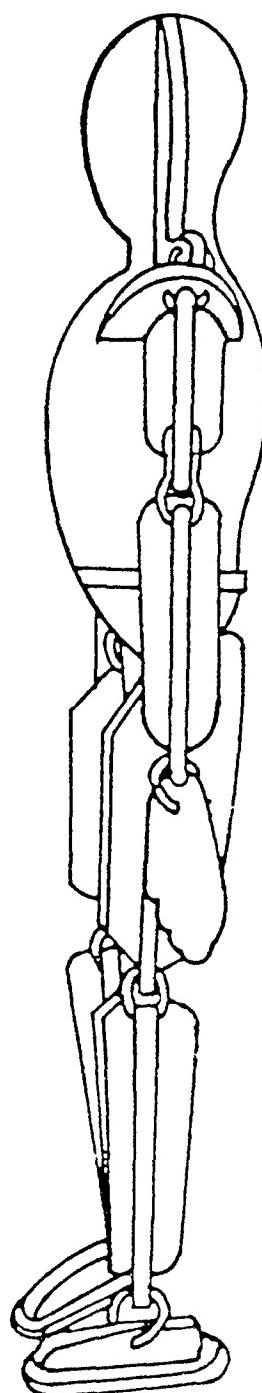
- Hole Size \rightarrow Mass
- Penetration Depth \rightarrow Velocity
- $P(I/H) = f(M, V)$
- ComputerMan simulation



PLYWOOD MANIKIN



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PLYWOOD MANIKIN METHODOLOGY

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LABORATORY COMMAND

Prob[Incapacitation | Hit]

$$P(I | H) = 1 - \exp \left[-a \left(M_p V_S^{\alpha-b} \right)^n \right]$$

where:
 M_p =fragment mass in grains
 V_S =fragment striking velocity in feet/second
 α, a, b, n =curve fitting parameters.

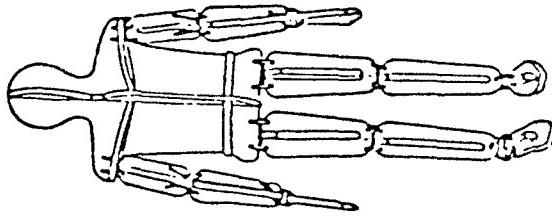
$$M_p = \left(\frac{A_p}{K} \right)^{\frac{3}{2}} ; \quad V_S = k_1 \left[\frac{\left(A_p / t \right)^{k_2}}{M_p} \right]$$

where:
 A_p =fragment presented area in square inches
 K =fragment shape factor in $2^{2/3}$
 t =fragment penetration depth in inches
 k_1, k_2 =curve fitting constants

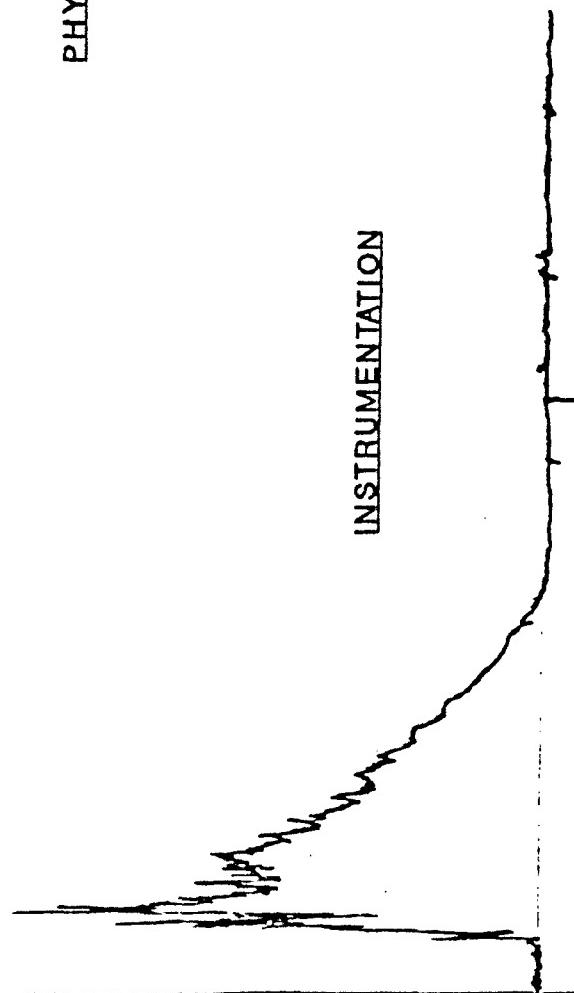
For Multiple Hits:

$$P_{Total} = 1 - \prod_{i=1}^{i=n} [1 - P_i]$$

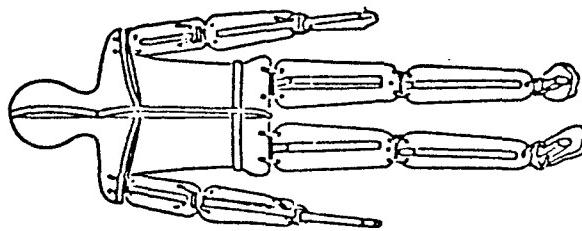
where: P_i is the $P(I | H)$ value for the i^{th} fragment.



CREW CASUALTY ASSESSMENT PROCESS



PHYSICAL MEASURES



Probability of Incapacitation, $P(I/H)$

Crew Position	Dummy Type	Main Pen	Spall	Blast	Therm	Accel	Toxic Gas	Total
DRIVER	A	0.00	0.00	0.30	0.00	0.00	0.00	0.30
COMM	P	0.00	0.00	0.38	0.00	0.00	0.00	0.38
GUNNER	P	1.00	0.00	0.30	0.00	0.00	0.00	1.00
LOADER	P	0.00	0.00	0.34	0.00	0.00	0.00	0.34

INTEGRATION OF CREW CASUALTIES INTO WEAPON SYS VULNERABILITY

DAL Prescribes System LOF for Injured Crew, e.g....

Two Crewman Lost

	<u>Mobility</u>	<u>Firepower</u>
Commander & Gunner	.38	.83
Commander & Loader	.32	.77
Commander & Driver	.37	.73
Gunner & Loader	.24	.72

Crew Casualties Incorporated into System M & F Calculation..

<u>Critical Function Lost</u>	<u>Mechanism</u>	<u>M</u>	<u>F</u>	<u>K</u>
Crew (Gunner: 1.00; Driver: 0.30; Commander: 0.38; Loader, 0.34	P/O	0.34	0.55	0.00
Gunner's Primary Sight	S	0.00	0.75	0.00
Intercom System	S	0.30	0.30	0.00
	---	---	---	---
		0.54	0.92	0.00



OUTLINE

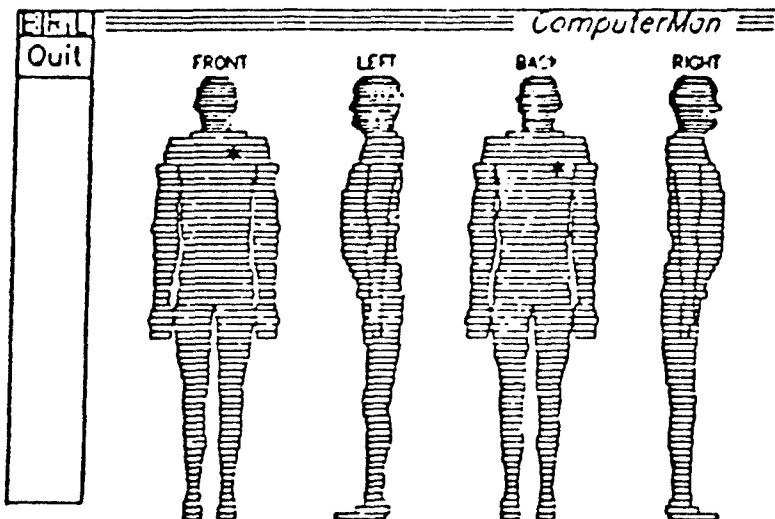
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BRL ComputerMan Modeling System

- Brief Overview
- “Discrete” vs. “General” P(I/H)
- P(I/H) vs. $P(I^{100}/H)$
- Probability of Survival
- References

ComputerMan Model



Features:

- Simulates penetration process
- Assesses resulting wounds
- Determines resulting disability, $P(I/H)$ or survivability
- Single or multiple wound
- Single, grid or point burst shots
- Handles steel, Al, W frags
- Graphical interface

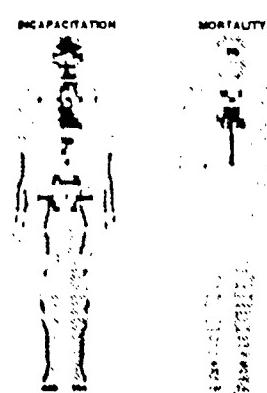
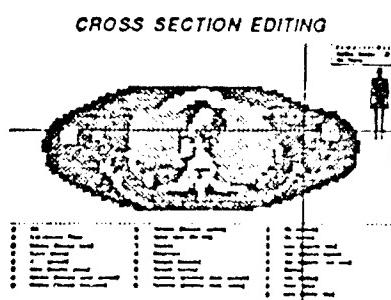
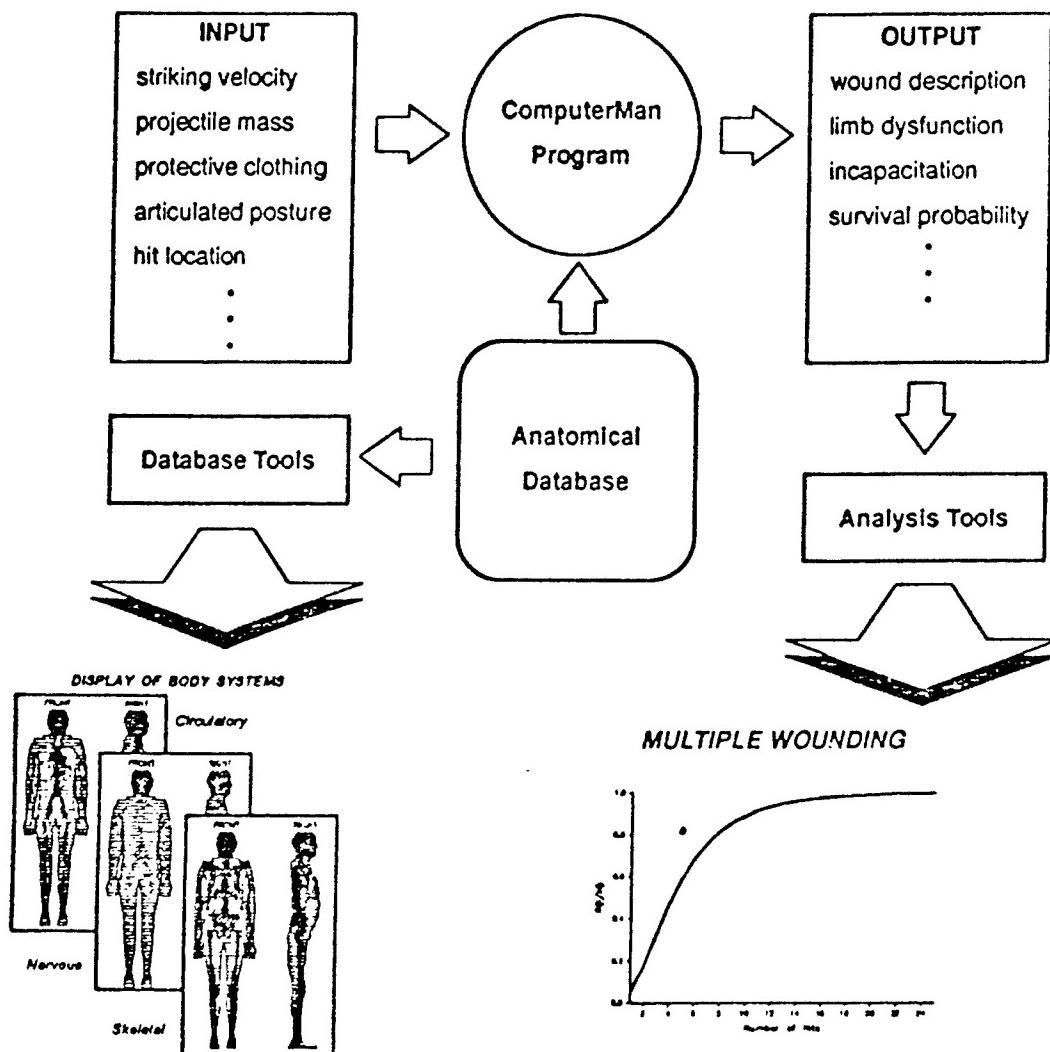
Applications:

- Specific/discrete (not generalized) assess.
- Vulnerability reduction (e.g., body armor)
- Special analyses (e.g., partial pen.)

Methodology:

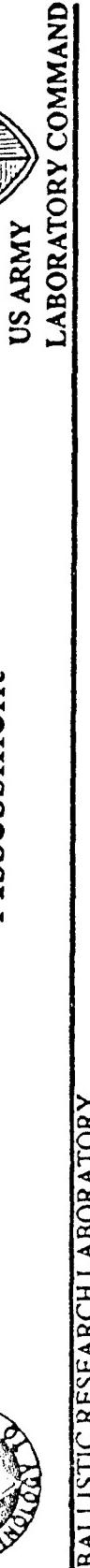
- Specify initial conditions, projectile & characteristics

ComputerMan System



Personnel Vulnerability/Survivability

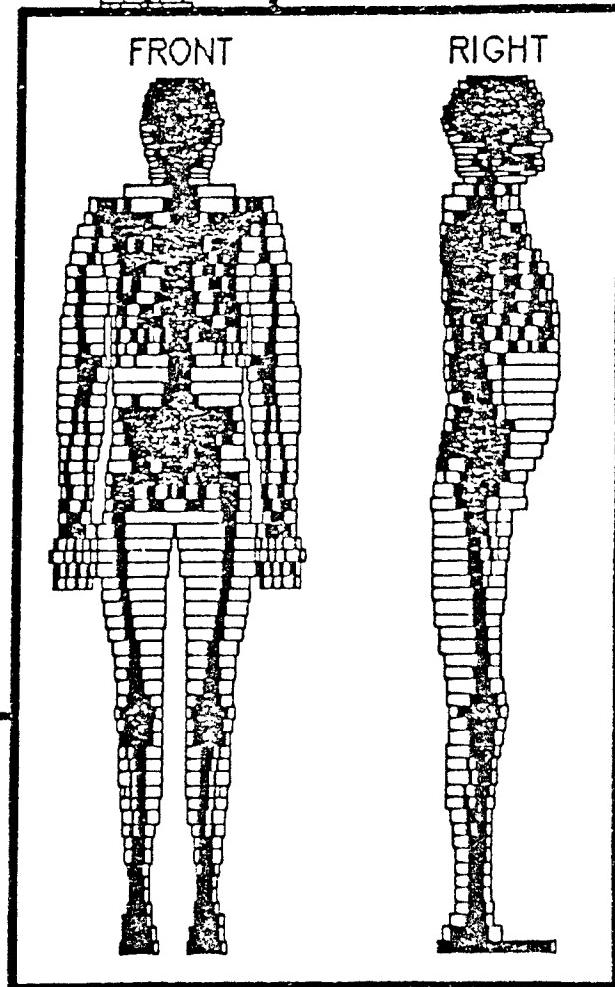
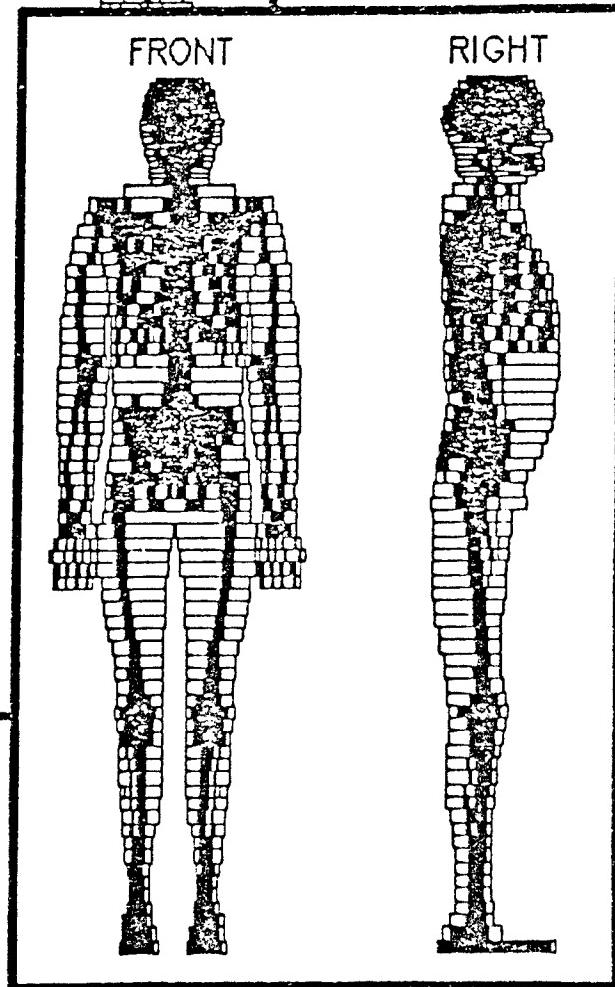
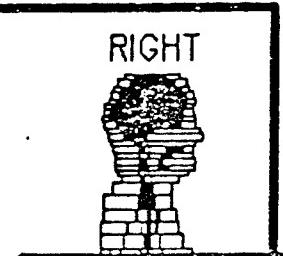
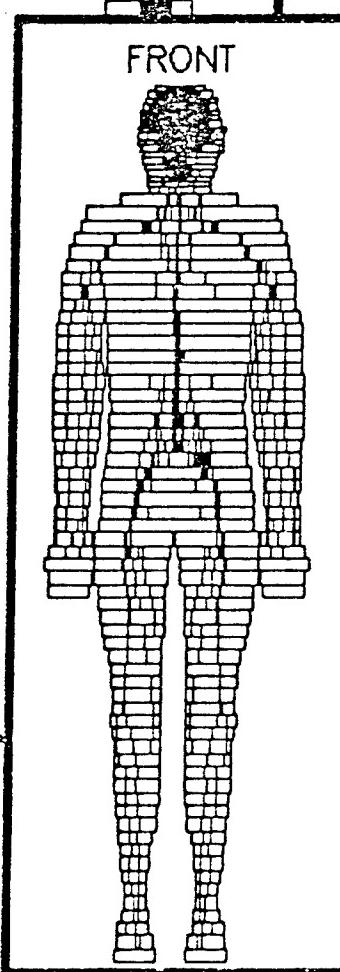
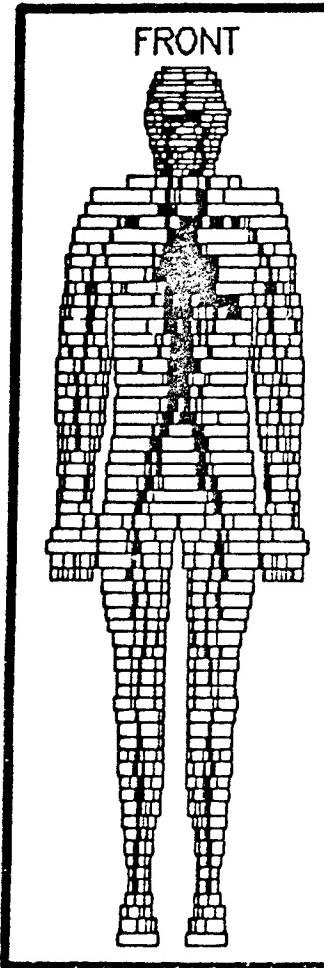
Assessment



BRL ComputerMan Modeling System contains an Anatomical description of the Human Body

- 108 Horizontal cross sections
- 280 Unique Tissue Types Identified
- 80,000 Data Cells

DISPLAY OF BODY SYSTEMS



Nervous

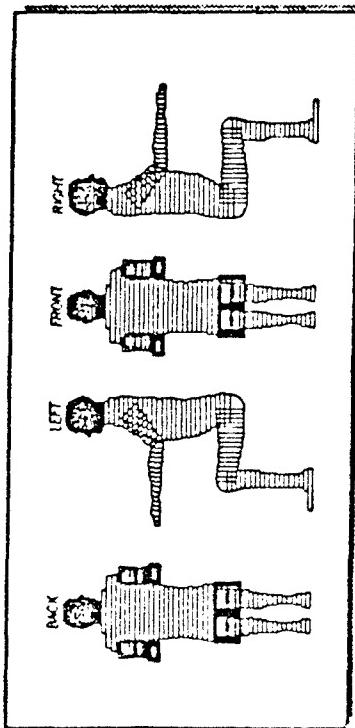
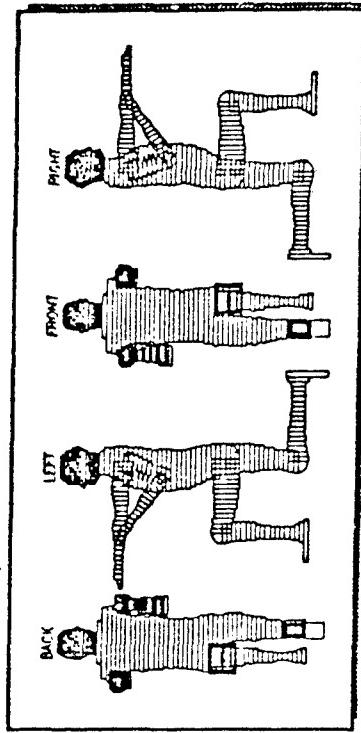
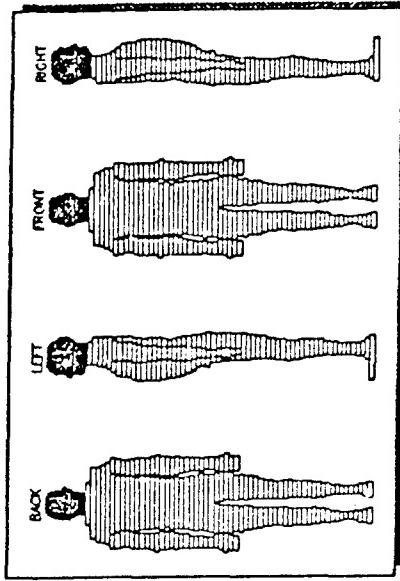
Skeletal



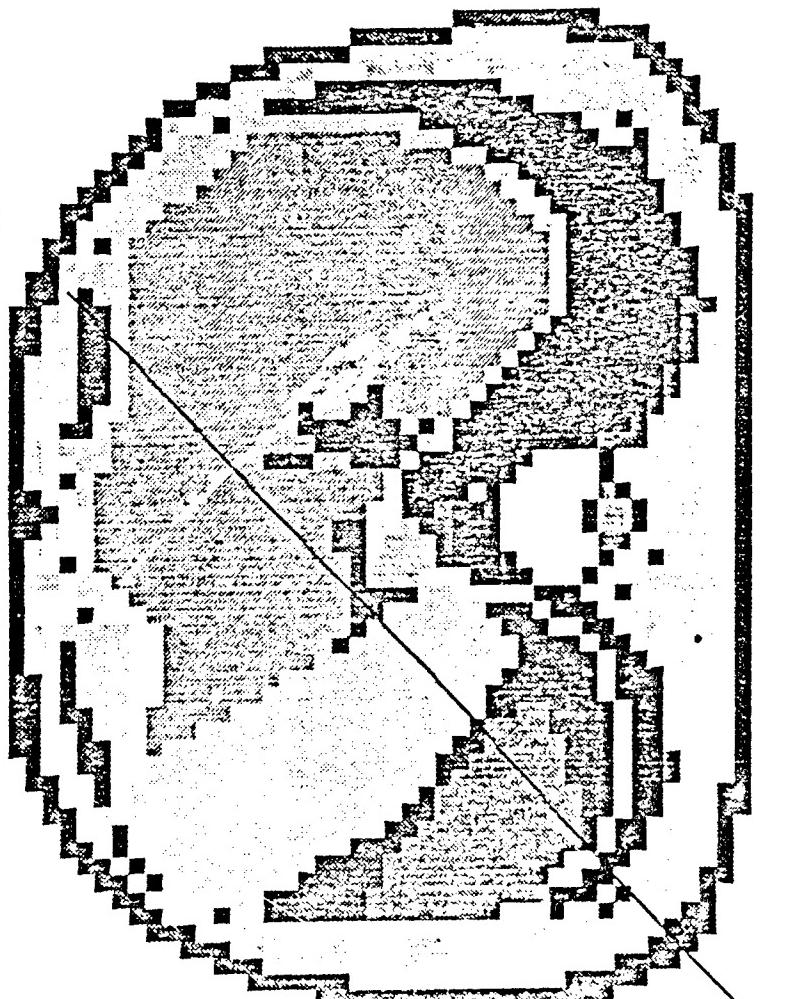
Articulated Postures

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- Man may be placed in
- Standing
 - Sitting
 - Crouching
- Positions



Comparative
Section Number
28
Upper Abdomen



Shotline

- | | |
|--------------------------------------|------------------------------|
| ■ Skin | ■ Lung (inferior lobe) |
| ■ Subcutaneous Tissue | □ Vertebra (thoracic lamina) |
| □ Vertebra (thoracic body) | □ Diaphragm (left) |
| □ Vertebra (thoracic spinal process) | □ Rib (abdominal) |
| □ Spinal Cord (T1-T12) | ■ Vein (azygos) |
| ■ Esophagus | ■ Artery (internal mammary) |
| ■ Diaphragm (right) | ■ Artery (intercostal) |
| ■ Sternum | □ Thoracic Duct |
| | □ Pericardium |
| | □ |
| ■ Liver (exterior) | ■ |
| ■ Spleen | □ |
| ■ Muscle (abdomen) | ■ |
| ■ Aorta (abdominal) | ■ |
| ■ Vein (hepatic) | ■ |
| ■ Artery (inferior phrenic) | ■ |
| ■ Vein (inferior vena cava) | ■ |

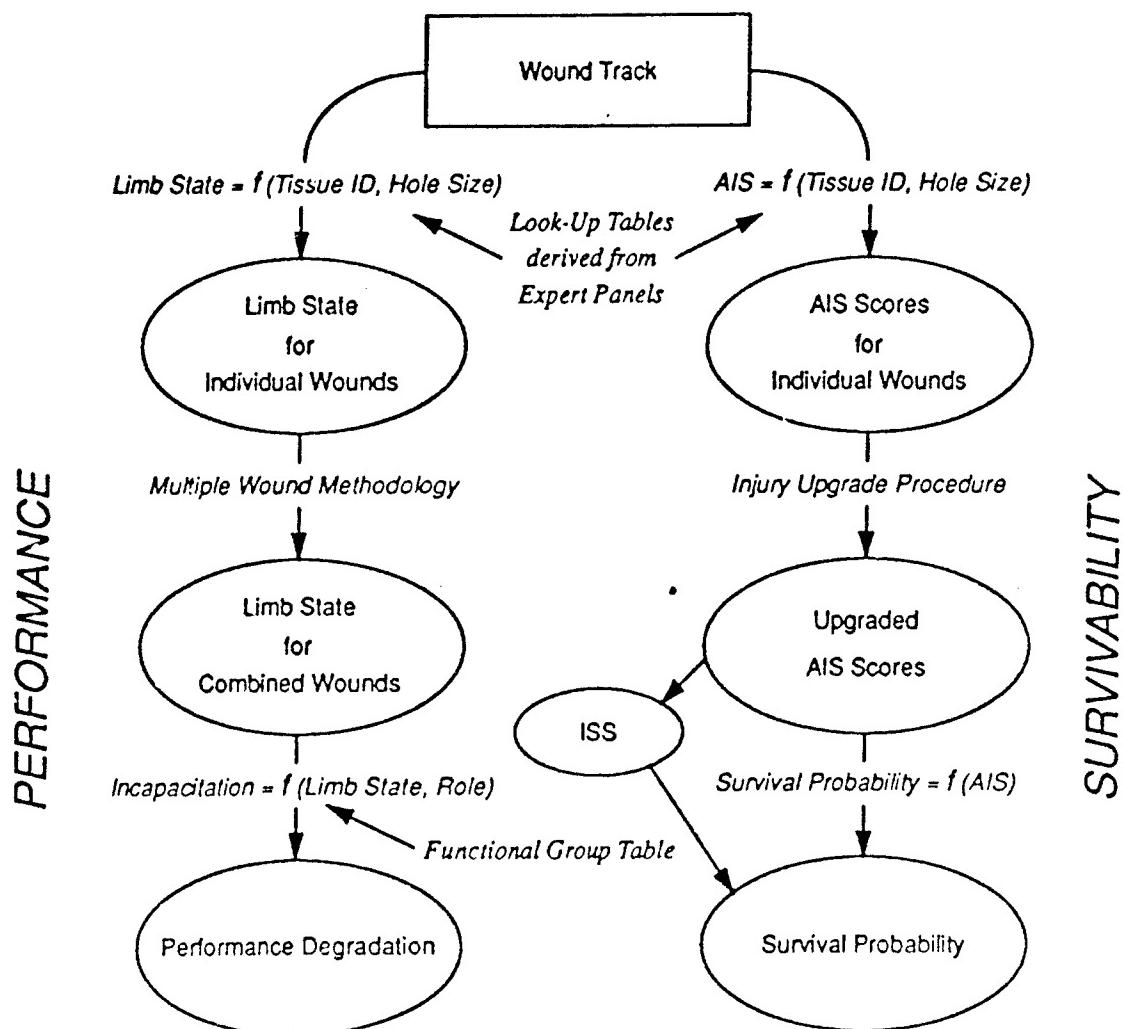
ComputerMan Methodology

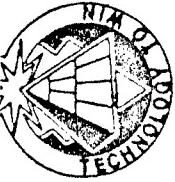


BALLISTIC RESEARCH LABORATORY

- 1 - Initialize and Set Fragment Parameters
- 2 - Enter Shotline Entrance and Exit Points
- 3 - Identify all Cells and Tissues Encountered along the Shotline
- 4 - Compute Striking Velocity at each Organ Interface
- 5 - Compute the Hole Size in each Organ Encountered
- 6 - Describe Effect upon Limb Function from each Organ Hit
- 7 - Determine Total Effect upon Limb Function from all Organs Hit
- 8 - Map the Overall Limb Dysfunction into Percent Incapacitated

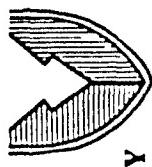
Methodology for Determining Performance and Survivability





Personnel Vulnerability/Survivability

Assessment



BALLISTIC RESEARCH LABORATORY

General Method

- 16 Functional Groups (= Limb States)
- No Differentiation between "Left" and "Right" limbs.

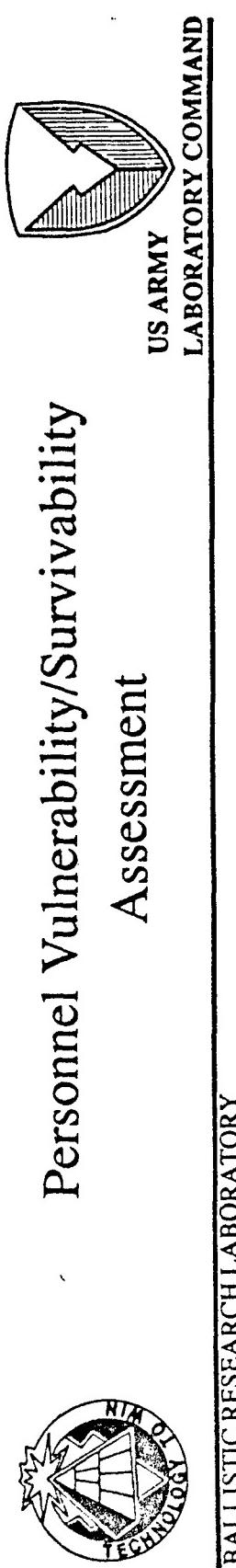
ComputerMan Discrete Method

- 81 Functional Groups
 - 4 Limbs, 3 situations {N,F,T}
- Original 16 FGs remain same, All FGs are consistent
- Differentiates between "Left" and "Right" limbs
- Allows for Multiple wounding assessment



Personnel Vulnerability/Survivability

Assessment



General Method

Calculates a "numerical average expected loss of function value" over entire body region for 6 angles ($0^\circ, 60^\circ, 120^\circ, 180^\circ, 240^\circ, 300^\circ$)

ComputerMan Discrete Method

Calculates a true probability of 100% incapacitation from the discrete anatomical fragment hit location and angle of fragment attack corresponding to the empirical field data collected from the manikin.



Personnel Vulnerability/Survivability Assessment

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General Method

- Derives a “numerical average expected loss of function value” computed from 0%, 25%, 50%, 75%, and 100% expected loss of function
- Not a Probability
- A misnomer that has been sanctioned by historical misuse

ComputerMan Discrete Method

- Derives True Probability
- Derives probability of 100% incapacitation



Personnel Vulnerability/Survivability Assessment

BALLISTIC RESEARCH LABORATORY
US ARMY
LABORATORY COMMAND

The bottom Line ...

- $P(I/H)$ - an "Average Expected Loss of Function Value"
and not a True Probability. Additionally, $P(I/H)$ is used in Vehicle System Vulnerability Models as a True Probability of 100% Incapacitation.

- $P(I^{100}/H)$ - "Probability of 100% incapacitation given a hit".
Meets Requirements of Vehicle System Vulnerability Models:

- "True Probability"
- Probability of 100% incapacitation



Personnel Vulnerability/Survivability

Assessment

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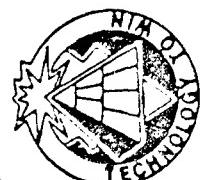
General Method

Does not Address Soldier Survivability Issue

ComputerMan Discrete Method

- Permits Calculation of Probability of Survival
- Probability of Survival based on extensive Civilian Medical Injury Databases

- Abbreviated Injury Score (AIS)
- Major Trauma Outcome Study (MTOS)
- Injury Severity Score (ISS)
 - ISS is correlated to Mortality
 - Survivability = $1 - \text{Mortality}$



Abbreviated Injury Scale

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6 Digit Code

Body Region

- 1 - External
- 2 - Head
- 3 - Face
- 4 - Neck
- 5 - Thorax
- 6 - Abdomen & Pelvic Contents
- 7 - Spine
- 8 - Upper Extremity
- 9 - Lower Extremity

A/S Severity Level

- 1 - Minor
- 2 - Moderate
- 3 - Serious
- 4 - Severe
- 5 - Critical
- 6 - Virtually Unsurvivable
- 9 - Unknown

Specific Anatomical Structure

Organ or Specific Area
Assigned in Succession

Level of Injury

Within Anatomical Structure
Assigned in Succession



Survival Probability

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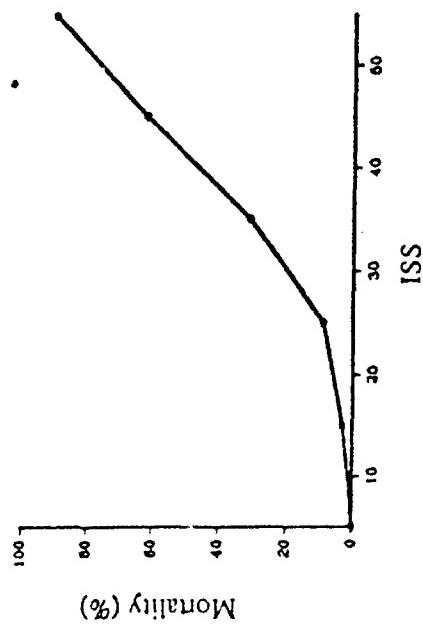
AIS → ISS → Survival Probability

Procedure for Computing Injury Severity Score (ISS)

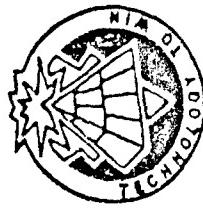
- Assign AIS Score to each Injury
- Find Highest Rating for each ISS Body Region
- Sum the Squares of the Three Highest Ratings

ISS Body Regions

- 1 - Head or Neck
- 2 - Face
- 3 - Chest
- 4 - Abdominal or Pelvic Contents
- 5 - Extremities or Pelvic Girdle
- 6 - External

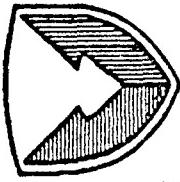


Correlation between ISS and Mortality



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TECHNICAL REPORT BRL-TR-3141

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COMPUTERMAN USER'S GUIDE

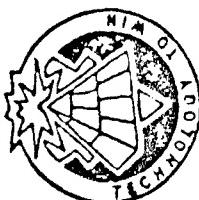
RICHARD SAUCIER

AUGUST 1990

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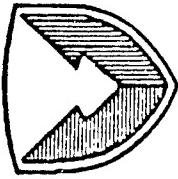
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MEMORANDUM REPORT BRL-MR-3929

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THE MODELING AND APPLICATION OF
SMALL ARMS WOUND BALLISTICS

DAVID N. NEADES
RUSSELL N. PRATHER

AUGUST 1991

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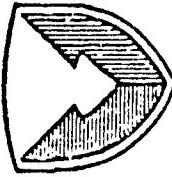
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MEMORANDUM REPORT BRL-MR-3908

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IMPROVED METRICS FOR
PERSONNEL VULNERABILITY ANALYSIS

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